WEARABLE VIBROTACTILE STIMULATION: HOW PASSIVE STIMULATION CAN TRAIN AND REHABILITATE

A Dissertation
Presented to
The Academic Faculty

By

Caitlyn E. Seim

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Interactive Computing

Georgia Institute of Technology

May 2019

WEARABLE VIBROTACTILE STIMULATION: HOW PASSIVE STIMULATION CAN TRAIN AND REHABILITATE

Approved by:

Dr. Thad Starner, Advisor
College of Computing
Georgia Institute of Technology

Dr. Gregory Abowd
College of Computing
Georgia Institute of Technology

Dr. Elizabeth Mynatt
College of Computing
Georgia Institute of Technology

Dr. T. Richard Nichols
School of Biological Sciences
Georgia Institute of Technology

Dr. Desney Tan
Microsoft Healthcare
Microsoft Research

Date Approved: March 26, 2019

Nothing will work unless you do.

Maya Angelou

To all who love and support me.

ACKNOWLEDGEMENTS

Thank you to my advisor, mentors and committee members. I would also like to thank Dr. Steve Wolf, Dr. Samir Belagaje, Dr. Edee Field-Fote, and Dr. Sarah Callahan (from Emory University, Grady Memorial Hospital, and the Shepherd Center) for their expert advice on the scientific protocol and clinical tests.

I would like to thank PT Solutions Morningside and Physio Midtown for donating their time to help take clinical measurements free of charge. Thank you also to the Atlanta Center for the Visually Impaired for helping provide Braille documents and embossing. Finally, I would like to thank the students at Georgia Tech whom I had the privilege to mentor.

This material is based upon work supported, in part, by the National Science Foundation under grant No. 1217473 and an NSF Fellowship. My work is also supported by a Microsoft Research PhD Fellowship and a Georgia Tech GVU Seed Grant.

TABLE OF CONTENTS

LIST OF FIGURES

SUMMARY

Wearable computing devices can now provide haptic stimulation for extended periods of time in the background of other tasks. I suggest that this wearable tactile stimulation may be advantageous to haptic training and rehabilitation. Extended periods of stimulation can provide intensive repetition, and stimulation without attentional focus can be used for passive learning. For therapeutic applications, extended wear can enable hours of stimulation outside a clinical environment and in the background of daily life.

Ambient stimuli can enable passive learning: training while users are occupied with other tasks. Most research on this topic has used audio or visual stimuli, and few have explored the use of *haptic* stimuli for passive learning. In this dissertation, I present evidence that **wearable vibrotactile stimulation can help train a variety of skills** including those involving rhythm, simultaneous actions, and various body parts. This work also provides essential **guidelines on how to construct wearable computing systems that apply this technique to practical problems.** Results suggest that this passive training method may allow users to recall dozens of motor actions with little practice and learn challenging skills with less difficulty.

Wearable vibrotactile stimulation may also help re-train sensorimotor functions, for example, diminished arm function after a stroke. Stroke can lead to chronic physical disability in the limbs. In fact, stroke is the leading cause of adult disability in the US. Preliminary evidence suggests that peripheral tactile stimulation may facilitate limb rehabilitation, but current methods for applying this technique are limited to laboratory settings.

Currently, there is no device available to administer and study therapeutic tactile stimulation for extended periods of time or outside the clinic environment. I present **a low-cost, wireless wearable device to provide tactile stimulation therapy** and an initial randomized controlled trial in stroke survivors over 8 weeks. Results suggest that **wearable vibrotactile stimulation may also be a powerful tool to reduce disability after a stroke.**

CHAPTER 1

INTRODUCTION

Passive learning is knowledge acquisition through stimuli that are in the periphery of attention. For example, while focused on an unrelated task, people can gain knowledge about other things through sounds in their environment [75]. Most research on this topic has used audio or visual stimuli, and few have explored the use of *tactile* stimuli for passive learning. Wearable computing devices can now provide tactile stimuli for extended periods of time in the background of other tasks. I suggest that ambient tactile stimuli may be a powerful tool for skill acquisition, motor learning, and may introduce new information in the area of neuroscience and motor memory storage. Huang et al. introduced the concept of "passive haptic learning (PHL)" (or "passive tactile learning"), but prior research has focused exclusively on teaching songs on the piano using this technique. There are currently no guidelines on how to apply this training method to teach other skills, or guidance on what applications are suitable for using this technique.

This dissertation provides evidence that more than just a simple melody on the piano can be taught using passive tactile stimulation. I present evidence that **repeated vibrotactile stimulation can help train a variety of skills** including those involving rhythm, simultaneous actions, and various body parts. This work also provides essential **guidelines on how to construct wearable computing systems that apply this technique** to practical problems. Results suggest that this passive training method may allow users to recall dozens of motor actions with little practice and learn challenging skills with less difficulty.

Wearable vibrotactile stimulation may also help users re-learn functions, for example, diminished hand function after stroke. Stroke and other central nervous system (CNS) injuries lead to chronic physical disability in the limbs. In fact, stroke is the leading cause of adult disability in the US. However, current clinical treatment options are limited to strenuous exercises and only about 50% of survivors are eligible to participate. Preliminary laboratory evidence in animal and human subjects suggests that peripheral tactile stimulation may facilitate sensorimotor recovery after CNS injury, but current methods for applying this technique are limited to laboratory settings [71, 91].

Currently, there is no device available to administer and study therapeutic tactile stimulation for extended periods of time or outside of the clinic environment. A wearable computing device could provide tactile stimulation for extended periods of time in the background of a patient's daily life. I suggest that wearable tactile stimulation may be a powerful tool for sensorimotor recovery and spasticity relief. Here, I present an **initial device and randomized controlled trial using tactile stimulation therapy** in stroke survivors over eight weeks. Results suggest that intensive passive **tactile stimulation may indeed help reduce disability after a stroke.**

This work leads to my **thesis statement: Repeated vibrotactile stimulation, without movement or attentional focus from the user, can help teach a plurality of discrete actions and their associated meanings and reduce sensorimotor disability after a stroke.**

The studies conducted to examine this thesis have led to several contributions:

- I show that a plurality of discrete actions or cues and their associated meanings can be rapidly taught using repeated tactile stimuli. This result is illustrated through several studies of teaching Braille, typing systems and codes.

- I present several computing systems that enable passive tactile learning and introduce guidelines for their design.

- I present evidence that repeated passive tactile stimuli can help users with stroke improve upper limb sensorimotor function. This method is illustrated through a preliminary clinical trial on stroke survivors using this technique at home.

- I present a wearable computing system that enables therapeutic tactile stimulation outside the clinical setting, on-the-go or at home, and for extended periods of time.

The experiments in this thesis focus on what vibrotactile stimulation can enable, by using a wearable device to apply the stimulation at length and in the background of other tasks. In Chapter 3, I use passive stimuli to teach discrete **groups of simultaneous actions** and the **information they encode**. Participants were able to learn the entire Braille alphabet in less than four hours. Chapter 4 focuses on teaching **complex sequences of actions**. I apply this technique to piano teaching. Chapter 5 covers how passive haptic training can **improve skill performance**, even when given a visual guide that provides the answers. This work aims to help users practice typing and other motor skills with less effort. I examine how commercially available wearable devices can be used for haptic training in Chapter 6; this work also shows how **rhythm or temporal sequences** and **their meanings** can be taught passively using tactile stimulation. Chapter 7 introduces background on stroke and rehabilitation in preparation for Chapter 8. In Chapter 8, I develop and test a wearable device and novel stimulation method to help stroke survivors **recover upper limb function**. Chapters 9 and 10 discuss main findings and future work.

CHAPTER 2

BACKGROUND: PASSIVE LEARNING AND HAPTIC TRAINING

2.1 Active Haptic Training

Haptic technology interacts with the sense of touch. These technologies interact with the body using methods such as tactile stimulation (i.e., vibration), limb manipulation (i.e., with a robotic structure or exoskeleton), and interactive force feedback (i.e., variable force of a joystick).

Haptic systems have been used to help individuals learn and perform skills. Williams et al. produced a review of these haptic systems and better defined different methods that they use [146]. Using a haptic system for practice before task performance might be considered **haptic training**. This method traditionally requires the attention of the user and may include limb manipulation [32, 45, 55, 90, 151]. Other systems provide *instructional* **haptic feedback** during task performance – guiding or cuing the user for example. For instance, this feedback may be giving users directions or correcting an incorrect motion [63, 70, 79, 131, 137, 138]. Haptic systems also commonly provide *realistic* feedback to simulate objects or effects in virtual environments (Figure 2.1). Such feedback can be key to simulating situations like tissue manipulation in robotic surgery or object interaction in video games [25, 67, 102]. This feedback can help with learning but is designed to be realistic rather than instructional.

2.2 Vibration and the Sensory Receptors

Haptics research has led to devices that provide tactile feedback using techniques including vibration, skin-drag, electrical stimulation, and light touch, among several others [65, 132, 135]. Each of these techniques have their advantages and disadvantages regarding

Figure 2.1: Haptic training using physical guidance and active feedback. *Image from NASA [141]. Creative Commons.*

hardware, mobility, interaction and resulting perception.

The use of vibration in haptic systems is often limited to providing alerts and simulating objects, likely because it is difficult to convey complex or continuous information using this modality. However, vibrotactile feedback has a number of advantages. It is low-cost and can be simple to drive using circuitry. Tactile actuators are also easy to integrate into mobile and wearable devices, and because vibration does not physically manipulate the limbs, it does not physically interfere with other concurrent tasks.

The response of human sensory receptors to vibration has been studied. The body has several types of cutaneous (skin) and proprioceptive (muscle and tendon) sensory organs which all respond differently to sensory stimuli.

In the skin, there are four main types of **cutaneous sensory *mechanoreceptors*** [69]. The Pacinian corpuscles (FA2) are located deep in the skin and respond preferentially to deep pressure and high-frequency vibration. These receptors have large receptive fields and are "rapidly adapting," meaning that they respond only to the onset and offset of a stimulus. Meissner corpuscles (FA1) are another type of rapidly adapting sensory receptor and have small receptive fields. These fibers respond to low-frequency vibration and brushing across the skin. Merkel disks (SA1) are "slow adapting," meaning they respond continuously to static or tonic stimuli. These receptors respond to sense tactile details and have small receptive fields. The Ruffini endings (SA2) are slowly adapting, respond to skin stretch and have large receptive fields. These cutaneous receptors respond to vibration. Pacinian corpuscles respond to direct vibration and vibration transmitted through the body at a frequency range of over 10-400 Hz (preferentially responding to around 200 Hz). Meissner corpuscles respond most to vibration at 30-50 Hz [69].

The body also contains **proprioceptive sensory fibers**. The muscle spindles sense stretch of a muscle and include types that respond in a continuous or dynamic manner. These afferent fibers respond to vibration up to about 220 Hz (type I) and 100 Hz (type II), respectively [14, 43]. Golgi tendon organs sense muscle tension, and some research suggests they respond to vibration during muscle contraction at frequencies of 20-120 Hz [43].

Vibration on the hand may reach all of these afferent fibers. At sufficient amplitudes, including those used here, vibration will be conducted through the skin to reach the various mechanoreceptor types. The distribution of certain mechanoreceptors on the hand is not uniform. Meissner corpuscles and Ruffini endings are more dense near the fingertips of the glabrous skin on the ventral (palm) side of the hand [68]. Pacinian corpuscles and Merkel disks are evenly distributed throughout this skin. Merkel, Pacinian, Ruffini fibers are present around hair follicles on the hairy skin of the dorsal hand [19]. Proprioceptive afferent fibers may be reached through hand stimulation by vibration conducted through bones and tendons.

Here I focus most stimulation on the proximal phalanx. For hand stimulation, this combines the practical and physiological considerations: leaving the fingertips free for normal use and snug fit, while still individually stimulating each finger. **The devices used in this work were designed to stimulate cutaneous Pacinian corpuscles** (which respond most to the high-frequency vibration produced using small actuators) which are not more densely populated at the fingertips. In addition, muscle afferents are likely also activated by stimulation at this location, **(dorsal phalanx) as stimulating away from the fingertip**

Figure 2.2: Passive learning can occur from background auditory, visual, or implicit information – such as audio from the television in this image. *Image from Pxhere [62].*

has more access to extensor tendons and bone not covered by significant flesh. Both of these structures may carry the vibration to muscles in the forearm. These afferent fibers provide proprioceptive sensory activation that occurs during normal movement. In fact, as mentioned by Cordo et al. , vibration produces enhanced proprioceptive activation, but does not include all components of sensory activation that occur with actual movement [29].

2.3 Passive Learning

Passive learning is knowledge acquisition through stimuli that are "in the background" and are not the focus of attention [75]. Research has demonstrated passive perceptual and motor learning from ambient visual [42, 144, 145] and auditory information, for example in Figure 2.2 [75, 153]. Similarly, implicit learning is a well-defined area of cognition whereby knowledge is acquired largely without the involvement of conscious top-down conceptual processes. Examples of this include speech acquisition through exposure and classical conditioning [33]. Learning occurs without the person's awareness and the knowledge is often "highly resistant to explication [111]." Research on this type of learning has shown that *continued exposure or practice* can imbue skills such as sequential motor actions [113]. Since some controversy remains as to the exact definition of implicit learning, especially when users later try to actively recall their skill, here we maintain the use of "passive learning" to describe skill acquisition without study.

2.4 Passive Haptic Learning

This thesis explores a form of haptic training: "passive haptic learning (PHL)" or "passive tactile learning." Like other forms of haptic training, instructional haptic cues help train users before skill performance is tested. Here, however, instructional cues are applied while users focus on unrelated tasks – making learning passive. Like other cases of passive learning and implicit learning, stimuli provide *continued exposure or practice*. [1]

Passive training has a number of significant potential benefits: passive haptic training may reduce practice time and help teach complex motor skills with less initial confusion and clumsiness. Limited research has been done on passive haptic learning. Prior work focuses on teaching short piano songs using tactile instruction. In this work, users wear a haptic glove while performing unrelated tasks. The glove uses vibrotactile actuators to "tap" one finger at a time in a short sequence (Figure 2.3). After a period of passive learning, users removed the glove and were able to repeat the sequence on the piano [59, 60, 73]. This work showed that tactile stimulation can enable passive learning. **Only a short sequence of key presses was taught using this method, but there may be significant potential in this technique.**

Figure 2.3: The haptic interface glove used in teaching piano melodies. *Image from Georgia Tech [99].*

[1] The term "passive haptics" is used to refer to physical properties of objects such as shape and material. In contrast, "active" haptics may influence users by actively stimulating or moving. Here, we use the term "passive" for "passive learning," meaning that stimuli are ambient or in the background. "Active" learning, on the other hand, requires the user's active attention and focus. Therefore "passive haptic learning," a term defined in prior work, refers to passive learning or training using haptic technology.

2.5 Contribution

Wearable devices can now easily provide tactile stimulation. **The wearable form factor allows stimulation for extended periods of time, providing stimulation in the background during other primary tasks.** Unlike robotic limb manipulation or interactive haptic feedback, tactile stimulation is unobtrusive and does not preclude other tasks. Yet the use of tactile feedback is largely focused on alerts and virtual reality.

How can we take advantage of wearable, tactile stimulation? **If the stimulus encodes information, tactile feedback may be able to help train complex skills.** But traditional learning and haptic training can be confusing and time consuming. I suggest that by applying the stimulation **repeatedly for extended periods of time while the user focuses on other tasks**, cognitive bottlenecks of initial learning and time required for initial practice can be reduced.

Prior work has shown that this *passive haptic training* is possible in a limited context. My work aims to **demonstrate passive tactile training in a variety of new contexts and enable others to apply this technique.** Not all skills can be taught using passive haptic training; however, my results suggest that this technique is a powerful tool for a number of applications. Here, I outline how passive tactile training can help teach motor actions and improve skill performance, teach users to associate sensations with meaning, and teach information that can be conveyed via haptics.

CHAPTER 3

TEACHING BRAILLE

In this chapter I present evidence that passive haptic training can help teach Braille. Prospective users of Braille are in critical need of a teaching aide, and this application presents new challenges in haptic interface design and passive learning.

Braille typing is a similar skill to piano – requiring the use of the fingers to perform simple actions (pressing keys). However typing on the Braille keyboard (used to produce tactile dots of Braille) is different and more complex than the piano songs that were previously taught using passive haptic training.

Here, I present two studies on passive haptic training of Braille typing – with the goal of addressing this real-world problem and learning more about passive haptic training. I hypothesized that instructional passive stimuli, if designed with a low cognitive load and efficient perception, could help train dozens of simultaneous motor actions and their associated meanings.

Passive Learning Challenges

A piano song is simply one short sequence of actions, whereas typing language requires knowledge of many **discrete actions and their meaning** (the key(s) required to produce each character). Prior work on passive haptic training has not explored teaching a plurality of discrete actions. Though this chapter focuses on the application of Braille, I aim to enable others to use the guidelines from this chapter to train other applications involving discrete motor actions.

Haptic Interface Challenges

The Braille keyboard is chorded, requiring multiple simultaneous buttons to produce one character. It is unknown how **simultaneous actions** should be conveyed through passive tactile stimulation. This skill also requires the use of both hands. Previous work taught skills to only one hand.

3.1 Motivation

39 million people in the world are affected by blindness. Learning to type the Braille system is time consuming and a major component of the rehabilitation and independence training for individuals who are blind or visually impaired. Braille is especially difficult to learn for those who lose their sight later in life, such as the aging population, wounded veterans, and the increasing number of diabetics. What's more, Braille instruction is neglected in schools; 40% of school-age children who are blind *or visually impaired* are considered illiterate. Overall, only 10 percent of those who are Blind learn Braille [8].

The National Federation of the Blind calls illiteracy among the Blind a "crisis" [8]. Because of a lack in certified teachers and bureaucratic barriers to providing education, blind and low vision students are not being taught Braille. For these individuals, though, Braille equates to reading and writing, and without this education, they are illiterate [10, 139]. The problem does not end here; Braille literacy directly correlates with academic success and employment (even in contrast with those proficient with screen-readers) [10], leaving 74% of blind individuals unemployed. Mainstreaming blind students in the public school system, where significantly less time is available for learning Braille, is another significant cause for this crisis; the influx of speech in technology is also causing neglect in Braille instruction. Listening alone is not enough, however, as research shows that Braille provides a critical advantage for students in learning math, grammar, language, spelling, and science [139]. Blind individuals, adults and students alike, even try to attend Rehabilitation Centers to gain these necessary skills for independent living. However, access to these facilities is difficult and requires a commitment to seven or more months of inpatient learning. There are only 12 such facilities in the United States, and for many, access to instruction here is also impossible because of financial or geographic constraints. Current technology for Braille instruction is limited to refreshable Braille displays and electronic Braillers. Methods used to teach Braille today involve tactile flash cards, block models of the Braille cell and hand guidance of the individual's fingers. Users first learn to read then type letters [9].

The lightweight and wearable system that I developed aims to teach Braille typing to those without access to instruction. My work aims to reduce learning time and difficulty by allowing individuals to passively learn while doing other tasks such as cane training, orientation and mobility or even tasks in their daily life or at home. With knowledge of the direct mapping between the keys of the Braille keyboard and the dots that comprise Braille, my system for teaching *typing skills* **can help individuals learn to read Braille as well.** This research aims not only to explore the subject of passive tactile learning, but also to create this system to aid Braille instruction.

3.2 Apparatus

This section details the wearable computing system that was designed to provide passive haptic training for both studies in this chapter. **Design decisions made within these apparatus sections can be used to inform future interface design for projects applying passive haptic training.** Based on testing, **stimulus design** and **teaching structure** are key to successful passive tactile training.

Wearable Device

The wearable haptic training system includes a pair of gloves with one vibration motor in each finger and a programmed microcontroller to drive the glove interface (Figure 3.1). The gloves are fingerless for optimal fit on different size hands, enabling the motors to rest flush near the base knuckle of each finger. Each motor is secured to the stretchy glove layer using adhesive and is located on the back of the hand (dorsal, non-palm-side) inside the glove. These gloves utilize eccentric rotating mass (ERM) vibration motors (Precision Microdrives model #308-100) and are driven high or left floating through a Darlington array chip attached to an Arduino Nano with buffered circuitry. They are driven at 1.3 g[1] amplitude and 200 Hz frequency. The microcontroller coordinates vibration timings and sequences to correspond with audio prompts for two phrases. For convenience, I created a Braille keyboard from two BAT^{TM} keyboards.

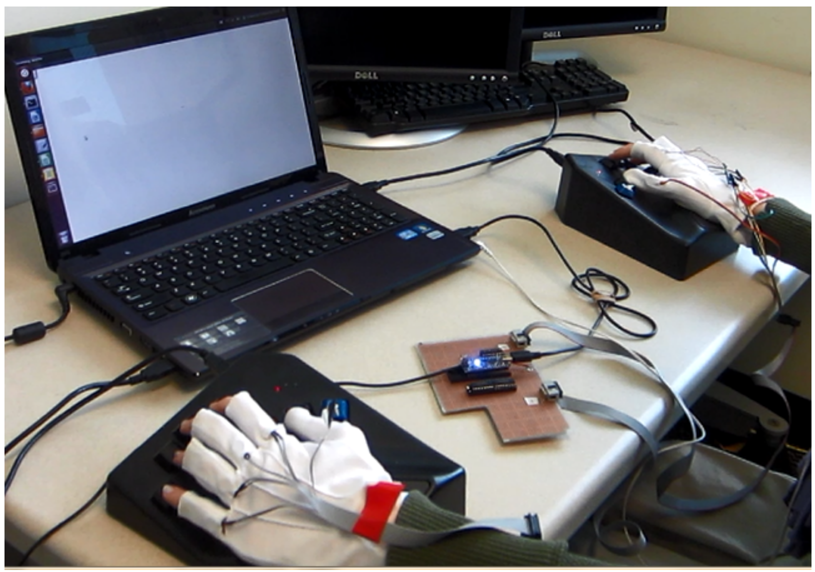


Figure 3.1: Haptic training system to teach Braille typing. Each finger can be stimulated individually by a vibration motor. Stimulation occurs when users are focused on other tasks.

Conveying Simultaneous Stimuli

It may be necessary for many applications of tactile training to indicate multiple body parts simultaneously (i.e., to convey tapping both feet or to define different cues based on multiple actuators). However, I suggest there is a perceptual barrier to simple simultaneous

[1]“g” throughout this paper refers to the constant *acceleration due to gravity* – used for vibration amplitudes. Force in grams is refereed to using “grams” – in reference to the Semmes-Weinstein monofilament exam

stimulation, and I present a workaround.

Braille typing is "chorded," meaning that it required multiple keys to be pressed simultaneously to make each character. In the process of designing a haptic interface to convey these simultaneous actions, I found that it was too challenging to perceive a plurality of stimuli at once. For this reason, I altered the stimuli system to present these stimuli groups, I applied a small temporal offset and presented the groups of stimuli sequentially instead of simultaneously. After this change, perception and learning using the system dramatically improved. For this reason I did a **follow-up study, presented in Appendix A, that further suggested that tactile perception of simultaneous stimuli is poor and simultaneous stimuli should be avoided if discrete recognition is necessary.**

Teaching Structure

Preliminary trials of teaching Braille typing passively had no teaching structure. Participants were exposed to letters at random, with only a few repetitions during a learning period. However, I suggest that repetition is key to passive training, just as repetition is key to traditional practice. **I hypothesized that teaching skills incrementally in parts, and thus providing ample, sequential repetitions of each part, would enable passive training.** I applied this teaching structure here and in other chapters.

This work aims to teach the key presses to type each letter of the Braille alphabet.

- In the first study of this chapter, a short group (phrase) of letters is trained.
- In the second study of this chapter, I use a pangram sentence to group letters into words and teach one word at a time.

This results in approximately 60 repetitions of the phrase or word during the learning period.

Stimuli

Vibrotactile stimuli are used to teach one word or short phrase at a time. Since Braille is typed using multiple keys for each character, each letter in the word is a short, grouped sequence of tactile "taps" – one on each of the 1-5 fingers used to type that letter.

An audio cue and a pause precedes each word and each letter. This pause and cue help separate each group of stimuli and associate meaning to the stimuli. The audio is presented before tactile stimuli begin, and does **not overlap**. Overlapping tactile and audio stimuli was found to be confounding in initial rounds of testing and related projects. It is conceivable that the audio could be removed if the user is told what word they are learning beforehand. Audio was found to be unnecessary for piano [73].

Actuators were activated for **durations of about 400 ms with very short pauses of 0-100 ms in between grouped stimuli** (for each letter) and 100 ms between letters of a word. Any stimuli in a letter were activated left to right on the hands, rather than in a random order. In addition, tactile stimuli of **adjacent body areas were separated by a small delay.** Based on pilot testing, active localization of stimuli was improved when a pause of 70-100 ms was inserted between stimulating adjacent body areas (fingers). Without this pause, stimuli tended to be recognized in the first location only. I believe this perception challenge would prevent passive training without adding the delay.

3.3 Study 1: Design and Methods

In this first experiment, containing 16 participants (ages 18-25), I examine the feasibility of teaching Braille typing skills passively. The study is a within-subjects design and each user participates in two sessions, each with a different condition. The order of these conditions is counterbalanced. The structure of each session is as follows:

- Pre-test
- Distraction task and training condition (30 min.)

- Testing

Conditions

Under the experimental condition (Passive Haptic Learning (PHL)), participants receive instructional haptic stimulation (details are in the apparatus section) to teach a Braille phrase in the background while focusing on their distraction task. In the control condition (Control), participants wear the gloves but have haptic stimulation disabled.

Measures

I hypothesized that users would improve on their knowledge of typing the Braille phrase after the passive training condition, measured as a reduction in uncorrected error rate (UER).

Pre-test

Baseline performance is determined through a typing pre-test. Study administrators use a verbal set of instructions and gestures to introduce participants to the keyboard and the nature of typing chords. At the start of the pre-test, participants hear audio of the phrase and feel the corresponding vibration sequence once before being prompted to try typing the phrase. Users are given one trial at typing the phrase during the pre-test. During this first vibration-guided pre-test, they are asked to pay attention to understanding the meaning conveyed by the vibrations, and to use the pre-test to understand how to correctly type chords on the keyboard. Results from this pre-test are used as a baseline for users' typing performance.

Post Test

After the distraction task, users are given a typing (post) test. During this test, participants are first prompted to type the entire phrase. They are given three trials to type the full phrase, three trials to type each word in the phrase, and three trials to type each letter in the phrase (presented in random order). Participants feel no vibrations during the test.

Braille Reading Quizzes

The goal of this research is to examine the potential of passive haptic training of Braille *typing skills*. **However, I hypothesized that this system could teach Braille reading as well,** because there is a direct mapping between the Braille keyboard and the dots of the tactile Braille cell. **The objective of haptic training is to train a tactile memory for the body parts (fingers) used to type each letter. However, users may be able to recall each sensorimotor memory and "translate" it into declarative information.** To test this theory I chose to add Braille reading quizzes in addition to Braille typing tests on the chance that participants could use the typing skills they passively learned to understand and read Braille as well. The quizzes were designed to determine if this transfer occurred or not. Recruiting from a pool of sighted individuals that do not know Braille; we understood that tactile perception may be difficult for these untrained individuals. For this reason, I included reading quizzes that use visual representations of Braille (**"visual quizes"**), in addition to "**tactile quizzes**" using embossed Braille representations.

At the beginning of both quizzes, instructions are provided that describe how the finger mapping of the keyboard aligned with the dots of the six-dot tactile Braille cell. Study administrators also demonstrate this mapping using our hands in combination with a verbal set of instructions to ensure participants correctly understand the relationship. The picture used on the quizzes to convey the mapping can be seen in Figure 3.2.

Visual Quiz This quiz is given at the end of each session, before the tactile quiz. The visual quiz is comprised of images of Braille cells with dots filled-in or left empty to illustrate what would be embossed on a printed Braille document. I created one question for each letter from the phrase they were assigned ("add a bag" or "hike fee"). *Add a bag* session users are quizzed on the phrase's letters in the consistently randomized order: d, g, b, a. For

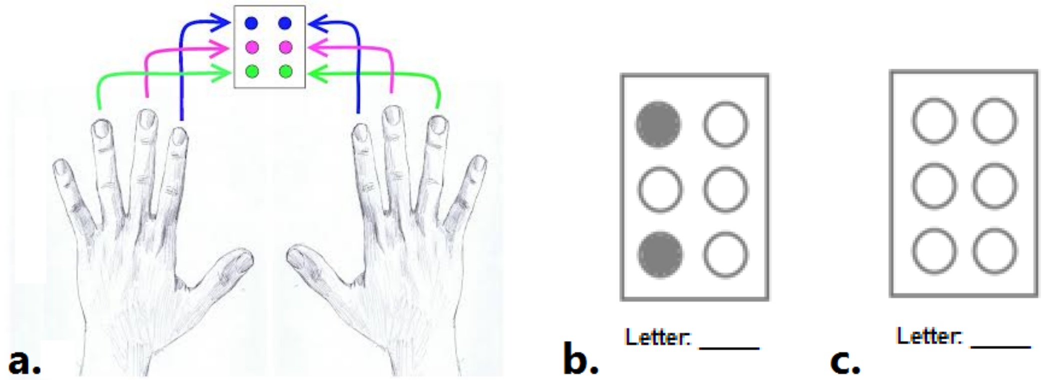


Figure 3.2: (a.) Mapping diagram on quizzes. (b.) Visual quiz question example. (c.) Tactile quiz answer sheet example.

the *hike fee* session they are quizzed in the order: f, i, e, k, h. Each question shows a Braille cell image (Figure 3.2) and asks users to write-in the letter it represents. This test may be the simpler of the two quizzes; while the tactile quiz combines Braille typing-to-reading "translation" with tactile perception. **This quiz makes participants extract *declarative information* from the *haptic stimuli* they received.**

Tactile Quiz This quiz is given at the end of each session. The Tactile Quiz was designed to understand whether the student can perceive the Braille cells with their fingers, and whether they can identify the letter from what they perceived. For this quiz, the subject places their dominant hand into a box, open only on one side, which contains a card embossed with the current letter from the quiz. This setup allows the subject to slide their hand in and access the Braille with their fingers without glimpsing the Braille on the card. Participants were given the same letters that appeared in their visual quiz but in a different consistently randomized order (b, g, a, d and h, e, f, I, k). After the student feels the Braille cell using their fingers, they mark a blank Braille cell on the quiz – three rows of two small empty circles (Figure 3.2) **to indicate what they perceived**. Subjects **also complete a blank with their identification of the embossed letter**. **Once users determine the dot configurations that they feel with their fingers, they must once again use *declarative information* to identify the letters. *Haptic stimuli* is the only source of information**

about Braille in this study.

Distraction Task

After the pre-test, subjects in both PHL and control conditions participate in a distraction task for 30 minutes. Both groups wear the gloves and ear buds during this time, but only the PHL condition receives passive haptic training stimuli in the background. **Haptic stimuli are the only thing providing information on Braille to the users. Users are told to focus only on the primary task (an online game) and give any audio and vibrations no attention. During the task, both groups are also asked to score as high as possible at the game task.** At the end of each distraction task period, their scores are logged.

The game Fritz! [47] was selected as the distraction task. This distraction task is a similar condition to *dual task training*, however participants are told to only focus on the distraction task so it is instead a *primary* task. Before the game, all subjects are provided with instruction on how to play. The goal of Fritz is to clear levels of blocks by aligning those of similar patterns through moving adjacent blocks. Figure 3.3 shows an example screen. For the purpose of the study, PHL groups are specifically told not to pay any attention to the vibrations or audio and to focus entirely on this distraction task. This game was chosen as a primary task because of several conditions: focus required to play, containing no reading/words, emit no sounds/mutable, and log a score. This task does make use of the fingers during training. Participants must use their fingers to click the mouse and navigate the game. These actions are unrelated to the training.

I wished to characterize performance on the task when users were focused solely on the game versus focused elsewhere at times. A student not in the study conducted three trials of his game play. Each trial consisted of 10 minutes of a focused session and a distracted session. During the focused session, the player played the game only. For the distracted session, the player was instructed to play the game while attending a television program as well. The player showed reduced scores during distracted game sessions by an average of

Figure 3.3: The game used for a dual or primary task during training.

19.36%.

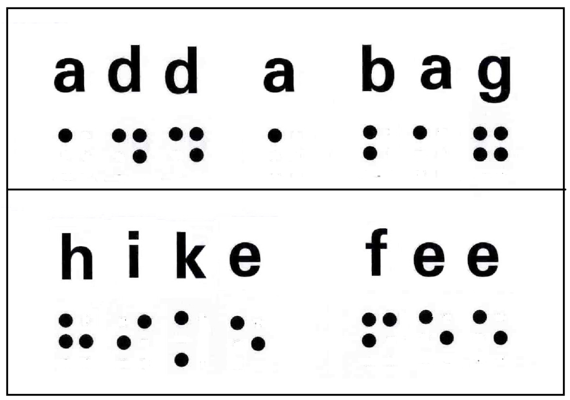


Figure 3.4: Phrases used in our first study.

Keyboard and Typing Software

The Braille keyboard used in this study consists of two Infogrip BATs. BAT keyboard inputs are translated into Braille keyboard entries. Key presses generate ASCII characters that are translated to the appropriate Braille value from a hash-map. Both "staggered" entry (pressing one key down at a time and then releasing all of them) and simultaneous entry (pressing all the required keys down at the same time) are supported. This technique produces a chorded input system that follows the Perkins Brailler standard as digital Braille keyboards do, such as Freedom Scientific's PAC Mate.

Typing software administers typing tests. The software prompts the user via audio and shows a blank screen. Upon each successful entry of a Braille letter or space, the screen displays an asterisk (to prevent learning during testing, and to let the user know that a character was entered) [126]. The software logs user input and performance, and calculates statistics like uncorrected error rate (UER) and words per minute (WPM) using formulae detailed by MacKenzie & Tanaka-Ishii [89].

Phrases

This study has two sessions per user. Each session focuses on one Braille phrase. Two phrases are used in this study: *"add a bag"* (AAB) and *"hike fee"* (HF). The order of these phrases is counterbalanced. These phrases were chosen for easy identification via verbal audio clips, in view of findings in previous related work [126, 130]. These phrases do not include homophones, difficult or little-known spellings, and have coherent meanings for easy understanding and memory. They were also chosen to be of comparable length (15-18 keystrokes), a length used in prior work on passive haptic training of piano [73, 126]. Finally, these phrases consist of Braille letters requiring no more than three keys each to type and have comparable complexity (repeated letters, 4 or 5 unique letters, containing words of 3-4 characters).

3.4 Results

With the aid of passive haptic training, participants significantly reduced typing error rates on the Braille keyboard, often reaching 100% accuracy. Users also learned to read nearly 75% of the Braille letters presented.

Typing

The typing software calculates uncorrected error rate (UER) and words per minute (WPM) [89] which is used for analysis of the participants' performance. As this study was within-subjects, paired t-tests are used to compare the effect of receiving training versus control. My a priori hypothesis is that training will improve performance on phrase and letter typing accuracy and visual and tactile recognition of letters, so no familywise multi-hypothesis correction was necessary. Threshold of significance was set to 0.05.

Comparing the typing error rate in the pre-test trial with the average error rate of the three phrase-typing trials on the post-test, the UER (uncorrected error rate) difference was calculated and graphed for each user's sessions. For both phrases, as seen in Figures 3.5 and 3.6, users reduced their typing error (increased accuracy) significantly after passive training sessions (31.55% and 42.78% on average).

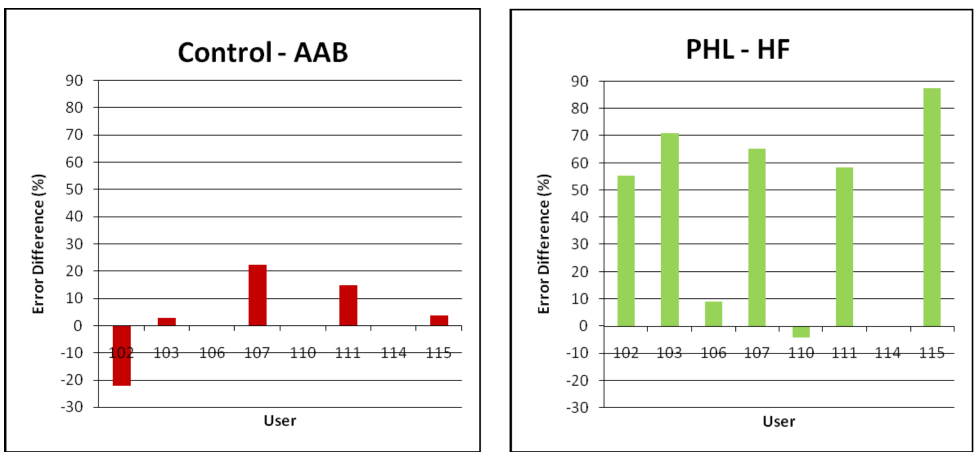


Figure 3.5: Typing accuracy improvements for participants who typed "add a bag" in their control session and "hike fee" for their PHL session.

This result was not true for control sessions, where minimal to no improvement (2.68%) was the norm for *add a bag* and increased errors (up 7.14%) was the norm for *hike fee*. These data are represented in the average improvements in accuracy for each phrase (Figure 3.7). A paired t-test suggests a statistical difference in the conditions: Participants given PHL have a larger AER difference (39.14) between pre-test baseline performance and post-test performance (M=37.16, SE=30.22) than people not given PHL (M=-1.97, SE=11.98; BCa 95% CI[22.0, 56.27], t(15) = 4.87, p=0.00001). When a participant was asked to type each single letter from the phrase, the number of correctly typed letters was significantly higher for PHL sessions than for control (Fig. 3.8).

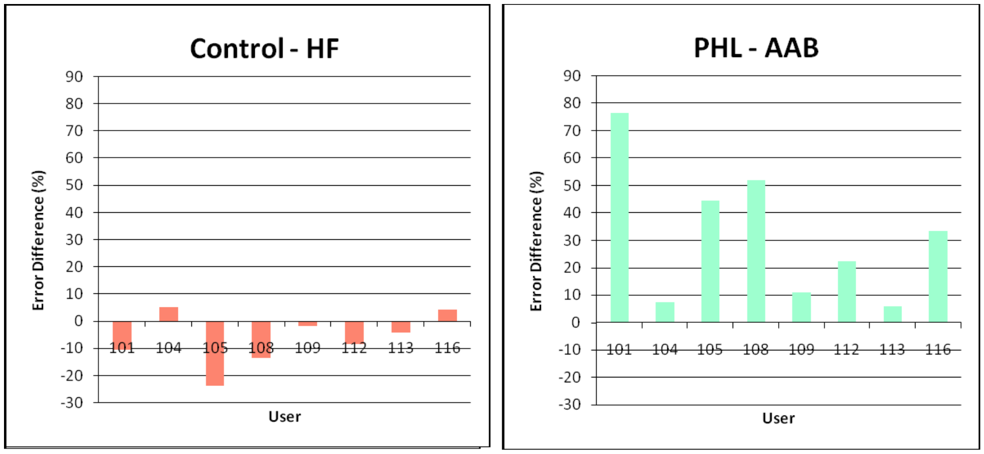


Figure 3.6: Typing accuracy improvements for participants who typed “hike fee” in their control session and ‘’add a bag” for their PHL session.

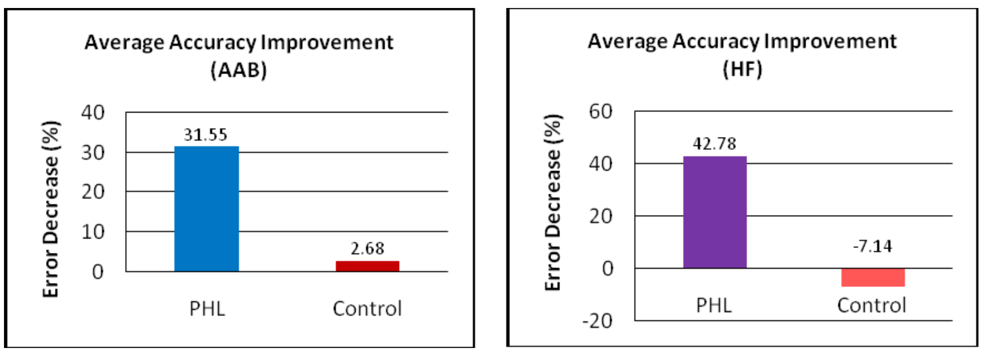


Figure 3.7: Average typing accuracy differences.

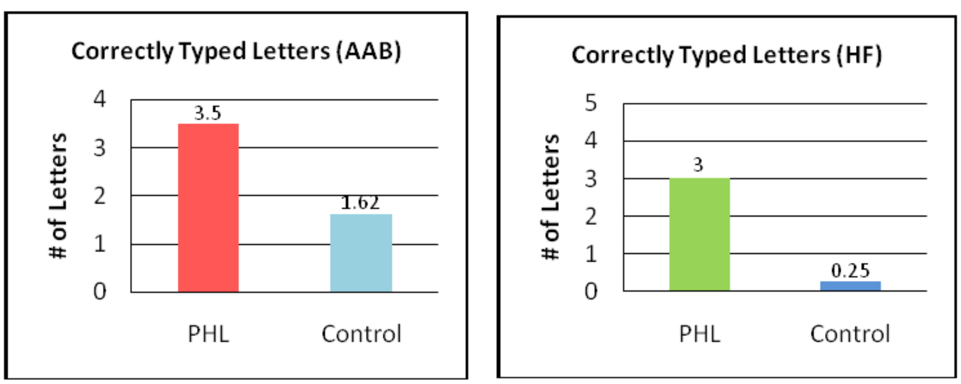


Figure 3.8: Letters typed correctly between conditions for both sessions.

T-tests illustrate that there is a statistical difference (2.31) in the number of correct letters typed between the conditions when participants are given PHL ($M=3.25$, $SE=1.69$) than people not given PHL ($M=.94$, $SE=1.12$; BCa 95% CI[1.33, 2.31]; $t(15) = 5$, $p=.00001$).

Distraction Task

All 16 subjects played the game for each PHL and control sessions and cleared up to level five during the 30 minutes. Results for performance differences were noisy due to the nature of the game, but average score differences between PHL and control were found to be within 10% as seen in the graph at the right. These results help to demonstrate and reconfirm the sensitivity of our chosen distraction task at monitoring user attention and mental resource sharing.

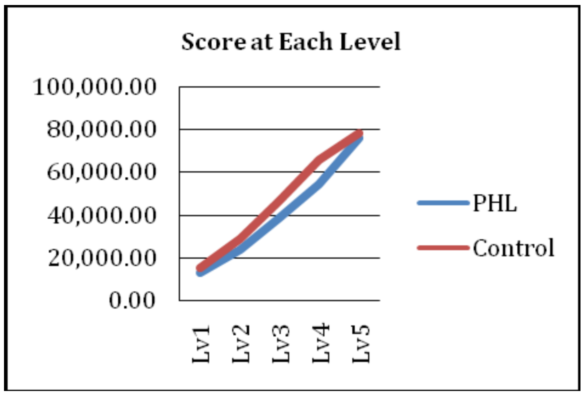
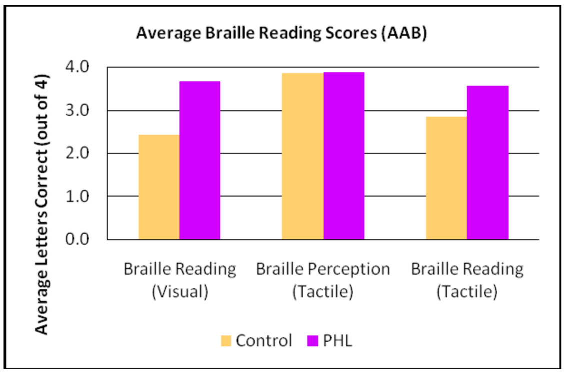


Figure 3.9: Distraction task score trends between PHL and control groups.

Reading Braille

Average score (letters identified correctly) is used to compare the tactile and visual quiz performance of participants that were given PHL and those that were not (control group). For sessions assigned either phrase, participants that were given PHL performed significantly better on reading (identifying) Braille letters. All users had near perfect tactile perception of the Braille cells; thus, PHL had little to no effect on the perception of letters on the Braille cards.

"Add a bag" Phrase Performance As seen in Figure 3.10 left, performance on the Braille reading quizzes was better in PHL than in control. Users were able to read 91.7% of the phrase's letters in Braille after receiving passive haptic training. Perception (of embossed Braille dots with the fingers) was nearly even between the groups, and on average, untrained users' tactile perception of the dot configurations was excellent (near 4 of 4 letters). Identification accuracy (# of correctly recognized letters) of the embossed (tactile) Braille was close to the same as identification accuracy during the visual test. If a participant was able to correctly perceive a Braille letter, their accuracy at correctly identifying that letter typically mirrored their ability on the visual quiz.



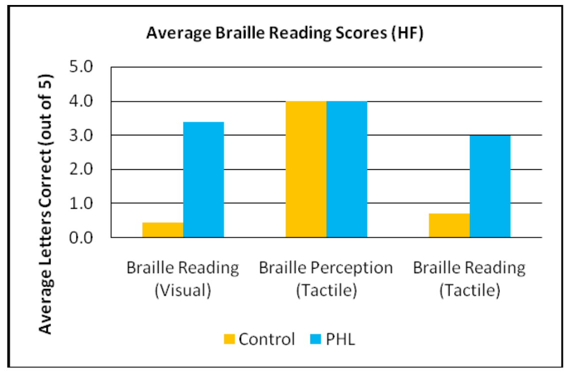


Figure 3.10: Reading scores between conditions for both sessions. Left bars are from visual quiz results, while right bars present results from the tactile quiz.

"Hike fee" Phrase Performance Findings from the *add a bag* quizzes remained consistent in *hike fee* sessions as well, with the PHL group far outpacing the control group. As also seen in typing scores, group differences were more evident in HF performance. The average number of accurately identified letters differed between the control group and the PHL group by three letters out of five. PHL participants again showed no difference in perception of Braille dots using the fingers (on the tactile quiz) from those that did not receive passive learning; while identification on the tactile quiz for the PHL group was on average 2.3 letters better. Passive haptic training participants did significantly better in reading Braille than the control group. This result is shown in Figure 3.10 right.

3.5 Discussion

Results of this initial study suggest that passive haptic training can teach users a plurality of discrete actions and their associated meanings (groups of keystrokes and the letters they produce) [120]. Typing test results indicate that users can rapidly learn to type Braille through vibration and audio stimuli. Study administrators observed users typing not only staggered input for each letter, but also simultaneous chorded input. This observation supports the idea that, using our current haptic system, users were able to grasp the nature of chorded typing.

A larger performance gap is found in *hike fee* sessions. This effect may be indicative of the phrase's higher difficulty. Though I designed phrases to be as well-matched as possible, *hike fee* has five unique letters and more vibrations which undoubtedly results in some increased difficulty. This difficulty lets users learn less of the phrase during the pre-test, the source of any knowledge in the control group; while PHL users could successfully passively learn the difficult phrase.

Distraction task performance helped confirm that users paid little attention to the vibration and audio stimulation during PHL. Score differences were minimal. Pilot studies were used to assess the game's sensitivity as a metric for distraction. In prior work passive training piano melodies, the audio was a larger distraction than the vibration [**te**]. Perhaps an improvement to study design would be to have the control condition also receive the same audio stimuli as the passive condition. In practice, however, our goal is to create a system by which users can acquire Braille typing skills with little perceived effort. If passive stimuli is a mild distraction while performing another task, our goal is still reached.

Remarkably, users could transfer knowledge learned in typing on the Braille keyboard to reading Braille. This acquisition of Braille reading skills through (passive learning of) Braille typing has intriguing implications. During the entire study, users were shown asterisks in response to each keystroke. **This uninformative feedback [126] means that**

users never see what they type on screen and had no indicators whatsoever of their correctness throughout the entire study. The only Braille information that participants received was guided by the haptic interface – an appropriate mechanism considering the target audience (users who are blind). I intend to make use of this finding, and our findings here on successful passive haptic training of Braille typing, to affect this audience. Application of this technology may be **used to help improve Braille literacy.**

Several components of our findings on Braille reading are of note. As could be expected, perception using the fingers was the same for both PHL and control groups. Interestingly though, our sighted, untrained pool of users were able to correctly perceive embossed Braille using their fingertips. The significant difference in reading error between those with passive learning and those given only the pre-test introduction coincides with results of user typing performance – further suggesting that users passively learned. **Encouraged by the results of this feasibility study, I expand this work to examine teaching the entire Braille alphabet passively.**

3.6 Study 2: Design and Methods

Above, I focused on the internal validity of whether passive haptic training can help teach Braille typing skills. Here, we are motivated by a larger goal: making and studying a system that enables passive training of the full alphabet in Braille.

I conducted a randomized, controlled, between-subjects study on eight participants (ages 18-28, sighted, native English speakers who did not know Braille). For this study, I increased the number of sessions and decreased the amount of time spent in each passive training period. This study consists of four visits, each approximately 24 hours apart. The structure of each visit is as follows:

- Testing: word 1
- Distraction task and training condition (20 min.): word 1

- Testing: word 1, word 2
- Distraction task and training condition (20 min.): word 2
- Testing: word 2

Conditions

Each participant was randomly assigned to either the PHL (passive learning) or control condition and received only that condition throughout the study. Participants assigned to the PHL condition receive passive training during each distraction task, while those in the control group receive only audio of the current word repeated on a loop. I chose to reduce the time for passive haptic training because oftentimes in the first study users encountered a ceiling effect (0% error in PHL) for the 15 keystroke phrase in 30 minutes.

Pangram #1

As detailed in the apparatus section, I use an 8-word pangram to divide the alphabet into parts. A pangram contains all 26 letters of the alphabet at least once, and forms a sentence in English. I train one group of letters (a word from the pangram) at a time, incrementally covering the entire alphabet (eight words = four visits, two distraction periods per visit).

The main pangram is "the quick brown fox jumps over the lazy dog." The pangram's words were used in order (the repeated "the" was omitted between "over" and "lazy"). This pangram was chosen over others for four primary reasons. The sentence is coherent and familiar to many English speakers, which enables users to remember and understand the phrase seamlessly. This pangram was chosen also because it uses non-ambiguous words with few homophones, an important consideration when using audio prompts [126, 130]. Words in the pangram are also of nearly equal lengths, with 3-5 letters and 10-17 vibrations each, remaining consistent with previously determined optimal lengths for PHL phrases [73, 126]. Finally, this sentence contains just eight unique words and repeats only four letters.

Measures

Tests assess Braille typing and reading throughout the study.

Pre-test

During the first pre-test of the study, users feel the full pangram #1 "tapped" on their fingers once. Participants then have a chance to type the full pangram as a baseline measure of knowledge (all users are novices). This initial vibration-guided trial, is followed by a standard pre-test present before all distraction periods. This pre-test consists of one trial each at typing the entire pangram #1 and then each word that it contains (presented in a random order). Pre-tests form the baseline in user performance before each distraction task (with or without passive training).

Post Test

Following each distraction task period, users are given a typing (post) test. Participants feel no vibration during the test and hear audio prompts provided by the typing software. The test consists of three trials at typing the session's word, followed by three trials typing each of the letters in that word (in a randomized order), and three trials at typing the full pangram #1.

The test then prompts users to type each word in a second "untaught" #2 pangram, giving them three trials for each of these words as well, before concluding with one trial typing the full #2 pangram. This pangram represents seven new words to type, by knowing individual letters in Braille. The #2 pangram is "when zombies arrive quickly fax judge pat." The same factors used to select the #1 pangram were used to choose this pangram: contains coherent meaning, similar word lengths (10-18 key-presses each), and contains few repeated letters.

At the end of the fourth visit, quizzes of all 26 letters are given. The full typing test consisted of three trials at typing every letter of the alphabet.

Braille Reading Quizzes and Tests

The structure and administration of the visual quizzes and tactile quizzes was the same as the first experiment. There was a unique quiz for the letters in each of the eight words in pangram #1. At the end of the fourth visit, quizzes of all 26 letters are given.

Distraction Task

Users in the PHL condition receive audio and vibration stimuli (designed to train a word in Braille) in the background during each distraction task. The same online game is used in this study as in the first study. **Users are reminded not to pay any attention to the vibrations or audio and to focus all their attention on doing their best at the game.**

Typing Software

The typing software (used in typing tests) provides prompts via audio. Prompts for pangram #1 consisted of only audio of the phrase or word. Audio prompts for #2 pangram (introduced in the post-test section) consisted of the word, followed by its spelling. This procedure was done for clarity of understanding on the part of the user, as this pangram is both uncommon and unfamiliar, and contains words with potentially unknown spellings. This method also emphasizes the composition of the word, allowing the participant to type the letters that they have already learned even though they have not learned the full/self-contained word.

The typing software was also updated to display letters rather than asterisks [126]. I made this change from displaying only asterisks to displaying letters typed because of the goal for the this study, which is to examine whether passive training can be used to teach typing of the entire Braille alphabet. The feedback may help reinforce learning and encourage confidence.

3.7 Results

Users receiving PHL outperformed those that did not. This finding was true for the full alphabet as well as for individual words.

Typing Phrases

Participants receiving PHL throughout their learning time showed greater improvements in performance, often reached perfect performance, and did so in less time than those without passive learning.

As illustrated in Figure 3.11, participants experiencing PHL were able to reduce their errors in typing the main pangram #1 phrase more rapidly and consistently. A single-factor ANOVA was also performed on the groups' pangram typing error rates over the study's 16 tests, and it found a statistical difference between the conditions (F=10.05, p<0.0001). Because of the informative feedback [126] used during testing periods, control users learned some letters through active practice trial-and-error; however, their learning was highly variable and more gradual. No users in the control condition achieved 0% error; while 3/4 users receiving PHL reached perfect performance on average before the final session.

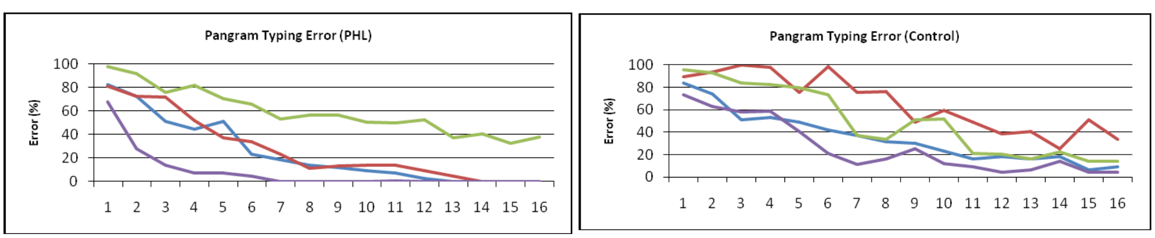


Figure 3.11: Pangram #1 ("the quick brown") phrase error rates for each user through all eight mini-sessions (pre-test and post test each).

These results suggest that passive training can be used to reduce learning time and difficulty for people learning Braille typing. Users not receiving PHL had significantly more variation in their number of typing errors. The near monotonic decrease in error for participants given PHL suggests that, as in previous work [60], passive learning may be aiding in passive rehearsal as well. Similar effects can be seen in user performance of the second "untaught" #2 pangram during the tests, as is illustrated in Figure 3.12. Single-factor ANOVA results for this pangram's (#2) typing error rates over the eight tests again found statistical difference (F=7.138, p<0.0001).

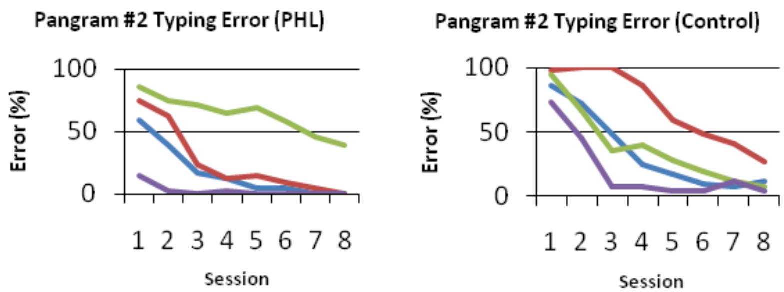


Figure 3.12: Pangram #2 ("when zombies") phrase error rates through all eight mini-sessions (phrase is only in the post test).

Typing Words

As in the first study, users receiving PHL illustrated UER differences between pre-tests and post-tests for each word. These improvements in PHL users' performance can be seen in Figure 3.13, which shows differences in error rates before and after passive instruction (or lack therof) of that word. Words at the beginning of the pangram are highlighted in the image because this performance difference is most visually noticable in initial sessions, before PHL users achieve 0% error on that word (while there is still room for improvement).

Distraction Task

From distraction task scores analysis, data show that the control subjects showed no significantly better average performance than PHL (3.03% difference between conditions). The more equitable performance between groups compared to our first study may be due to the addition of audio stimuli during the distraction task in the control group. This result suggests that users undergoing passive haptic training heeded instructions and did not pay attention to the vibration stimuli.

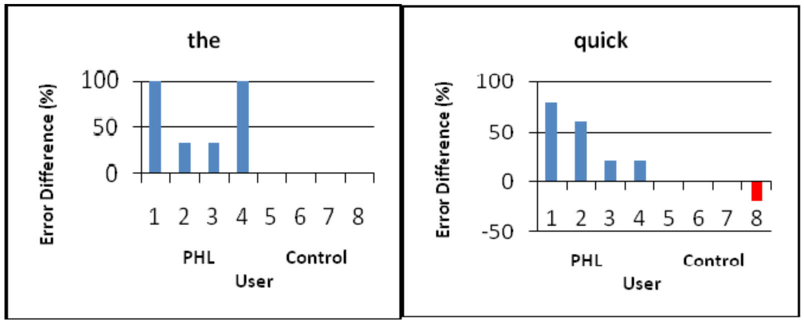


Figure 3.13: Pre and post test error rate differences for “the” and “quick” in the mini-session devoted to learning that word. PHL participants are labeled here as 1-4, whereas control participants are labeled 5-8.

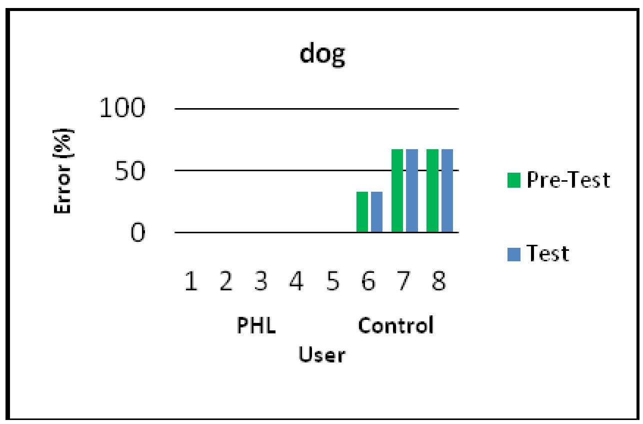


Figure 3.14: Pre- and post test error rates for “dog” in the mini-session devoted to learning that word. PHL participants are labeled here as 1-4, whereas control participants are labeled 5-8.

Reading Braille

As seen in Figure 3.15a, PHL participants also out-read users in the control group to achieve high levels of correct Braille reading in all words’ tests. Those who received passive haptic training correctly read within one letter of possible on average for each word’s quizzes; while control users identified fewer letters. Identification accuracy on tactile quizzes followed that of visual quizzes, as was also true in the first study. For 3-letter words in the PHL pangram the, fox, dog – as seen in the first study, perception accuracy was consistent between groups; however, words of 4-5 letters saw a difference in tactile perception accuracy between PHL and control users. This result is present in word quizzes, as well as the full quiz (Figure 3.15b). On the final quiz, PHL participants successfully read 93.3% of the Braille alphabet on average.

Questionnaire

A nine-question survey is given at the end of the study. Seven-point Likert scales are used on some questions (Strongly Agree (7) to Strongly Disagree (1)). Select results are tabulated below.

Question	PHL	Control (did not receive vibration)
"I did not actively pay attention to the vibrations while playing the video game"	7 (x4)	5 (x2), 7 (x2)
"Near the end of the sessions, I didn't pay attention to the vibrations at all"	7 (x3), 6 (x1)	3 (x1), 7 (x3)
"I focused only on playing the video game"	7 (x2), 6 (x2)	7 (x2), 6 (x2)

Figure 3.15: Questionnaire snapshot.

3.8 Discussion

In this expansion of our validity study, **users receiving passive haptic training succeed in learning to type the full Braille alphabet and reach 0% typing error within four hours.** Results indicate that those with training were able to complete learning more quickly. All users were able to learn some letters through trial-and-error during the tests, and I project that those with PHL reached 0% error rapidly by needing only to actively learn a few unknown letters (i.e., "z" before they were passively taught "lazy").

Full study results also suggest that typing practice can act as reading practice. Those receiving training again read more than those with only control (active practice). The gap in perceptive ability in those without passive haptic training is unexpected though. What is the reason for this added benefit from PHL? Perhaps those experiencing passive haptic training are able to match what they sense with their expectations and knowledge of the letters. What these results mean to future Braille instruction methods is yet unknown.

Results support the promise in a system for passive haptic training of Braille typing (and reading). This system shows promise to reduce time and difficulty for people learning Braille. One of the most cited causes for the crisis in Braille instruction is the growth of technology [8, 10, 139]. The idea that schools can neglect literacy instruction because of screen readers or audio recording is ubiquitous. Perhaps work in wearable, tactile interfaces and passive haptic training can redefine technology as a solution, rather than a cause of the problem.

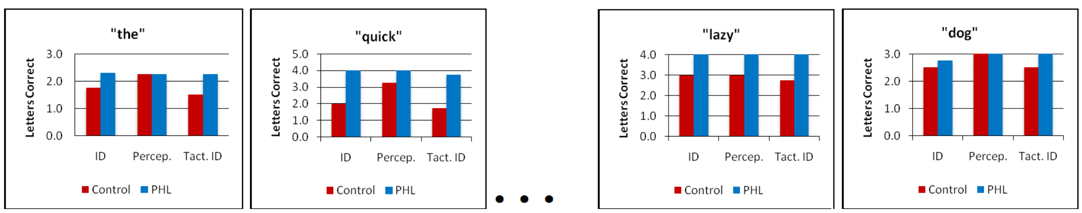


Figure 3.16: Reading scores for sessions 1, 2, 7 and 8's quizzes. Here, ID is visual Braille reading, "Percep." is tactile perception and "Tact. ID" is tactile reading score.

3.9 Conclusion

In this chapter I present a system and two studies. Passive haptic training of Braille is examined for validity and found to be robust. In an initial study containing 16 participants, users demonstrated significantly reduced error typing a phrase in Braille after receiving passive training versus control (32.85% average decline in error vs. 2.73% increase in error). These participants also gained reading skills through their typing skills, ultimately able to recognize and read 72.5% (vs. 22.4%) of Braille letters from the phrase. The apparatus for providing instructional haptic stimuli is also detailed here, including important considerations in the presentation of simultaneous stimuli.

In the second study, I passively train the full Braille alphabet in under four hours. Participants receiving training increased accuracy and knowledge more rapidly and consistently, with 75% of PHL vs. 0% of control users reaching zero typing error. By the end of the study, the experimental group was also able to read 93.3% of all Braille alphabet letters. These results suggest that passive haptic training using wearable computers may be a feasible method of teaching Braille typing and reading.

The goal of this chapter was to **apply passive haptic training to teaching Braille**, and in the process shed light on how to enable passive training. Braille typing consists of many discrete actions, each yielding a character, which is unlike the simple sequence of actions that was taught in previous work on passive haptic training for piano. In addition, Braille typing is a skill that requires use of both hands, and requires users to perform up to five simultaneous actions to yield each character. Results of my work show that passive training can help teach these **dozens of discrete and simultaneous actions** – revealing new potential in the technique. The wearable device and teaching structure that I developed in this work may help **enable others to apply this technique to training other skills.** In the following chapter, I convolve the findings of this chapter and that of prior work to train complex sequences of actions for advanced piano songs.

CHAPTER 4

ADVANCING PIANO

In the previous chapter, I demonstrated that passive tactile training can help users learn dozens of discrete motor actions involving two hands. In this chapter I apply this finding to an existing challenge in music training.

Prior work on passive tactile training has only explored training one-note-at-a-time, one-handed piano melodies [59, 73]. However, most piano songs include chorded notes and a melody performed by one hand with a harmony performed by the other. Learning these songs poses a challenge to students, as it is typically too challenging to learn both hands' pieces together.

Perhaps passive haptic training can overcome this learning challenge. Here I present a study on passive haptic training of complex piano songs. I hypothesize that passive haptic training will allow users to learn chords in music and enable practitioners to learn both the melody and harmony of a piano song simultaneously.

Passive Learning Challenges

Initial research on passive haptic learning focused on piano. This prior work showed that a sequence of single-finger taps could be trained using repeated tactile stimuli in the background of attention [60]. Most piano students would want to perform more complex pieces. Here, I expand findings on tactile training for Braille chords and instead teach a ***sequence of actions*** **that include two-hands and simultaneous actions (chords).** Though this work applies to piano learning, I aim to help others apply the findings presented here to similar applications: for instance, training a series of dance steps.

Haptic Interface Challenges

Here, I present and contrast two successful methods of teaching complex piano songs via haptics. One **teaching structure** breaks a piece into parts and teaches one hand at a time (as is typical of piano instruction), The other teaching structure breaks the piece into parts but teaches both hands together to examine if haptic training makes this usually confounding method possible. I use the same temporal offset method to convey grouped stimuli as was used in the previous chapter.

4.1 Motivation

Learning a musical instrument requires hours of practice, and every new song is a new sequence of notes. Passive haptic training may make it easier for practitioners to learn the actions composing each new song, allowing them to focus more quickly on the joy and artistry of playing. Results of previous work suggest that by wearing a tactile interface, students may be able to train or rehearse the "muscle memory" routine and reduce practice time or refresh their memory of a song too [92]. Young musicians might find this approach more rewarding than traditional focused and time consuming drills and, as a result, may be encouraged to persist in their education in the arts. Conversely, experienced musicians who are experiencing repetitive stress injuries due to practice might use passive training to reduce their active practice sessions to a minimum while maintaining skill. Prior work has taught simple melodies using this technique, but many music students will want to learn more complex pieces. Here I explore passive training of more complex piano songs.

There exists a dichotomy in the musical methodology regarding how to learn two-handed pieces. Typically, when learning a piece of music that uses both hands, piano students learn to play one hand and then the other before playing both parts together. However, music research literature views it as more advantageous to learn both hands together from the start [12, 39, 118]. Unfortunately, in teaching and practice, learning both hands together is viewed as largely too challenging – a stance with which research concurs [12, 39, 48, 118, 152]. Difficulty is posed by having to divide attentional resources between both limbs when learning the dexterity skill [12], resulting in widespread practice of learning one hand first, and then the other hand ("especially when playing a more complicated piece of music") [48, 152]. This common practice suggests that learning one hand at a time may make learning more palatable. Here I examine **whether passive tactile training can help** students learn both the left and right hand's parts simultaneously – overcoming this learning challenge and reducing time spent coordinating. I hypothesize that passive training of both hands together is possible, and thus allows for a more rapid reduction of errors in playing the piece as compared to learning one hand at a time.

4.2 Apparatus

This section details the wearable computing system that was designed to provide passive haptic training for this chapter. **Design decisions made within these apparatus sections may be used as guidelines for future projects applying passive haptic training.**

Wearable device

To provide instructional passive stimuli in this experiment, I designed a pair of gloves outfitted with a vibration motor (Precision Microdrives eccentric rotating mass (ERM) coin tactors) on the back of each finger near the knuckle. This placement and motor type was selected in compliance with previous research [60], and in consideration of additional perception studies conducted by me. 3.3V DC was used to provide the constant current used in this system, resulting in peak recommended vibration amplitude of 1.3 g and 200 Hz vibration frequency. The tactors were driven by TI ULN2003 Darlington array chips that buffer the systems microcontroller and provide the necessary amplified current. All motors are held flush with the fingers by the fabric making up the gloves. The gloves are fingerless to provide optimal fit for varying hand size.

Teaching Structure

In this study I compare two passive teaching structures for learning a two-handed musical phrase. I selected the phrases from Mozart's "Turkish March" and Vivaldi's "The Four Seasons, 2nd movement: Spring." These phrases were chosen to contain chords (simultaneous keystrokes) using both hands as well as dissimilar parts for both the left and the right hand.

In both teaching structures used here, the phrase is split into two parts. In prior work on passive tactile training, parts of about 10-17 stimuli are trained in 20-30 minutes. The success of this "dose" may vary depending on the complexity and number of actions being taught, and the clarity of the tactile interface. In pilot testing for this work, **more repetition of shorter parts led to more learning and less confusion.** Therefore, here, we compare two incremental/piecemeal teaching structures: users either learn the left hand portion of the song phrase followed by the right hand part, or they learn the first half of the song phrase (both hands together) then the second half of the phrase. See Figure 4.2.

Stimuli

Song phrases are fixed sequences of keystrokes. During passive haptic training, each finger used to play a key in the sequence is "tapped" using the vibration motors in the gloves. It takes about 15 seconds to stimulate the sequence, and then there is a 20 second pause before the stimulation repeats again. There are about 30 repetitions of the sequence during 20 min of training.

Stimuli in the sequence are grouped by timing – some keystrokes in music are supposed to be simultaneous (chords). Simultaneous keystrokes produce one auditory tone/note, just like individual keystrokes. Working from the previously established paradigm of using song music to accompany passive haptic stimuli, **each tone in the song phrase is played into the participant's earbuds, and the finger or fingers required to play this tone are then stimulated *sequentially (in view of the findings in Chapter 3).*** Then the next tone is played and so on. This audio punctuates the haptic stimuli: sequences yielding chords are broken-up by tones while keeping stimuli temporally tight, and users may have understanding of the tones to be expected when they "type" on the piano keyboard.

Actuators were activated for durations of about 400 ms with very short pauses of approximately 100 ms in between grouped stimuli on adjacent fingers (for chords). Any stimuli in a tone were activated left to right on the hands, rather than in a random order.

4.3 Study: Design and Methods

Eight participants (ages 20-30) with no knowledge of piano and conducted a within-subjects study to compare two passive training structures [122]. Each user attended two sessions during which they are passively trained on one of two music phrases under a *different teaching structure* each time. The study is counterbalanced for phrase and condition. Each session is divided in half, and each half focuses on one part of the song phrase. The structure of each session is as follows:

- Testing
- Distraction task and training condition (20 min.): part 1
- Testing
- Distraction task and training condition (20 min.): part 2
- Testing

Conditions

The conditions examined here concern how the haptic gloves passively teach participants. All users receive passive training for one part of the song phrase during each distraction task, but the way the phrase is divided depends on condition:

1. "LR" condition: users learn one hand's part followed by the other's (as piano students typically learn)

2. “Sync” condition: users learn both hands together (as they would perform the song)

Figure 4.1 shows how the music relates to the conditions: the phrase is split according to the different conditions.

Figure 4.1: One music phrase used in the study (from “Turkish March”). Divisions show what parts were learned during what condition’s first and second learning period (i.e., parts 1 then 2 for the synchronized condition or left then right for the one-hand-at-a-time condition).

Measures

I hypothesized that users would be able to perform a musical phrase with more accuracy (measured using a Dynamic Time Warp) after passive training, and that haptic training in the “Syncronized” teaching structure would result in greater reductions in error.

Both experiments tested users’ performance on a Casio lighted-keys piano keyboard. The piano was connected to a PC using a USB cable which enabled recording of what is played into MIDI format. The MIDI (Musical Instrument Digital Interface) format is a technical standard allowing discrete, clear data direct from the instrument with no noise generated by audio recording [133]. Each participant’s performances were recorded in MIDI format and evaluated using a Dynamic Time Warping (DTW) algorithm, to account for errors of substitution, insertion, and deletion. DTW evaluates the costs associated with various types of errors and attempts to minimize the costs, while finding the optimal match between two sequences. This metric is similar to the ISO standard for speech recognition accuracy.

Each session begins with a pre-test of the entire phrase to establish baseline performance. For the pretest, users watch the music phrase being played on the lit keys of the piano keyboard (the phrases are programmed into the keyboard by us). We then tell them where to place their hands and ask them to play what they know. They are given one try at playing the phrase during the pretest. All participants are piano novices.

After the pre-test, users spend 20 minutes receiving haptic training while focusing their attention on the distraction task. After the first distraction task and training, users are tested on their performance of the part of the song they learned passively. Users are given three attempts at playing the part. Before the first attempt, administrators play the song's audio, and before the last two attempts users are shown the piece played automatically by the piano itself, where the piano lights the corresponding keys as each note is played. This structure clarifies finger positioning and sharps during the piece.

During the second half of the session, there is a second distraction task and test (regarding the other part of the song phrase). The structure is identical to the first. At the end of a session, users are given a full test where they are asked to play the entire phrase (either by playing the left and right parts together, or the first part followed by the second part). As above, participants are shown the phrase played automatically by the keyboard before each of the three given attempts.

Distraction Task

The primary task from Chapter 3 [120] was used to occupy participants during the distraction period. During this time, participants wear the gloves and feel vibrations on their fingers associated with the music for the part of the song they are learning (see Apparatus section). **Participants are told to not pay attention to the stimuli and to focus only on getting a high score at the game.**

4.4 Results

Performance data was captured in MIDI format which represents what notes are played and on/off times. These data were then translated into ASCII for easier visual perusal and rapid, automated processing. A Dynamic Time Warping algorithm was used to analyze the distance between the sequences produced when testing users and the correct sequence of notes in each musical phrase. In the algorithm, each chord the user had played was either found to be entirely correct (a match) or was labeled incorrect (insertion, deletion, or substitution). For example, when looking for the chord “62-70-72” (three simultaneous keys) only an exact match would contribute no increase in distance (error); “62-70” or the like would be counted as entirely incorrect. This distance measure is then divided by the max length of the phrase or input to yield percentage error, as is the defined standard in text entry [89].

To examine the feasibility of passively teaching a sequence of two-handed key sets via haptics, without the active attention of the learner, we examine differences in performance error between the pretest and the average of the full post tests. In both conditions (LR and Sync), as well as overall, users demonstrated reduced error after receiving passive haptic training. Paired t-tests reveal that error differences between pretest and full tests (LR: M=33.60%, SE=0.0531; Sync: M=49.55%, SE=0.0547; All: M=41.58%, SE=0.0560) are significant (LR: $t(7) = 4.47$, $p < 0.0015$; Sync: $t(7) = 6.41$, $p < 0.00019$; All: $t(15) = 7.42$, $p < 2E\text{-}06$).

A Dynamic Time Warping distance measure was also devised for better analysis of correct song content in which chorded inputs may be recognized as fractionally (rather than entirely) correct. This measure was developed to be more sensitive to learning differences, in case users often did not learn or perform note groups (chords) correctly. Though non-typical in applications like text entry, where a similar Mean String Distance measure is used to examine only whether a letter is entirely correct even in high keystrokes-per-character

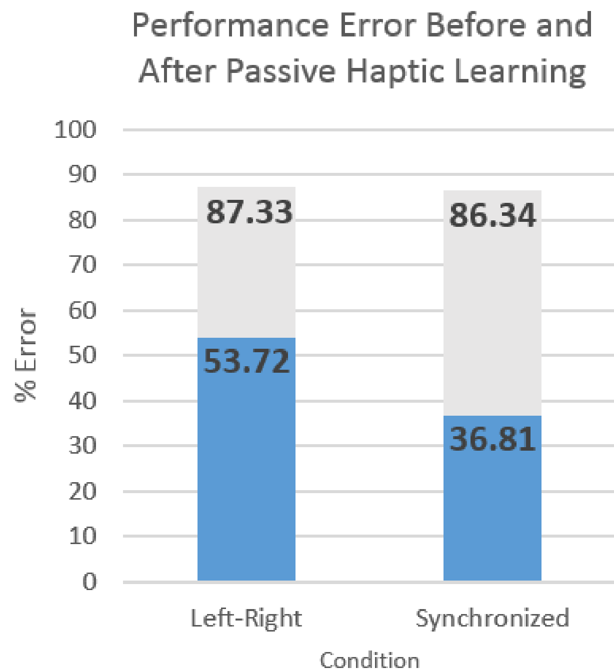


Figure 4.2: Performance error by condition. Before PHL (gray) reflects pretest performance, and after PHL (blue) reflects average full post test performance (using original DTW).

systems, applications such as this where learning, dexterity, and performance are evaluated may benefit from such a metric. The standard DTW measure was found to be reflective of learning (difference in performance) so this secondary measure was not needed in hypothesis testing. It too reflected a significant effect on error reduction between pretest (LR: M=82.76%, SE=0.0359; Sync: M=78.02%, SE=0.0412; All: M=80.39%, SE=0.0267) and full tests (LR: M=37.61%, SE=0.0398; Sync: M=27.40%, SE=0.0524; All: M=32.51%, SE=0.0331) when compared with a paired t-test (LR: $t(7) = 6.13$, $p < 0.0003$; Sync: $t(7) = 6.93$, $p < 0.0002$; All: $t(15) = 9.46$, $p <$ 1E-07).

Teaching structure conditions (LR or Sync) were compared for effectiveness. When users were given passive training in the Sync structure, they presented both better ultimate performance and improvement from the pretest. Ultimate performance (best full post test score (lowest error)) was examined for differences between conditions (LR: M=44.22%, SE=0.0562; Sync: M=23.12%, SE=0.0690) and compared with a paired t-test which suggests differences are significant (t(7) =1.98, p=0.0443). Improvement, which is defined as the error difference between the pretest and the average test performance, was also compared (LR: M=33.60%, SE=0.0531; Sync: M=49.55%, SE=0.0547), and significant differences were again found with a paired t-test (t(7) =-2.19, p =0.0322). See Figure 4.2.

Content-sensitive DTW reflected closer performance on the full test between conditions which illustrates an observed performance behavior difference: users who were in the LR condition learned and played the notes for each hand, but failed to synchronize them into the correct chord arrangements for the piece when tested. This partially-present content was reflected in lowered error rates for this group when using the content-sensitive metric versus the original all-or-nothing DTW measure. Further examination of performance improvements demonstrated no ordering effect or significant difference in song difficulty (errors by song). Comparison of performance on the distraction task (online memory game) showed no significant difference when compared with a paired t-test (t(7) =0.554, p=0.300).

4.5 Discussion

These results suggest that to learn a piece without reading music and with minimal practice, passive training can help. **Learning the piece using both hands at once is possible with haptic training and yields the best results.** It was also observed that users correctly played the notes of a chord together – despite each stimuli being presented sequentially for perception. Before passive training, users are told that each tone they hear is followed by stimulation on the finger or fingers to press that make that tone. With only this instruction, the interface successfully enabled users to parse the stimuli and seamlessly self-synchronize.

4.6 Conclusion

Here I present results teaching two-handed, chorded **piano songs** to novices using passive training. A study compared two teaching structures and found that, with the aide of passive haptic training, users can learn both left and right hand's tunes at once – enabling more rapid reduction of error.

Prior work on passive haptic training investigated teaching a sequence of simple actions for one-handed piano melodies. The previous chapter detailed how passive training can teach simultaneous actions involving two limbs. Here, I combine these findings to teach **complex sequences of actions**. Passive haptic training is currently ideal for discrete tasks such as piano, where each action is binary rather than continuous. This work shows how repeated, vibrotactile stimulation can **encode such discrete actions and train users one part at a time**. In the next chapter, I examine if passive haptic training can be used to help individuals not only learn a skill, but improve performance.

CHAPTER 5

IMPROVING PERFORMANCE ON KEYPAD TYPING

In previous chapters, I explored passive tactile training for initial learning of sequences and discrete actions yielding meaning. Here, I examine passive tactile training beyond initial learning – by designing a system to teach and improve typing speed on a labeled keyboard.

Many skills require extensive practice to improve performance, such as typing on the QWERTY laptop keyboard. Repetition is often the hallmark of this practice. Passive tactile stimuli can teach skills and provide extensive repetition; therefore, in this chapter I perform a preliminary test of whether continued tactile training may improve performance speeds.

Here I suggest a wearable computing solution for learning *and improving* keyboard typing skills. I hypothesize that passive tactile training can help teach users learn a spatial layout even when visual cues (key labels) are present, and I hypothesize that continued haptic training can improve their speed.

Passive Learning Challenges

Again here, I aim to teach discrete actions and their meanings – this time the key presses to type on a keypad. Here, however the skill is a **spatial task** where each action may require movement. In addition, both numeric keypads and QWERTY keyboards have each key labeled with the corresponding symbol so that even a novice can begin typing accurately immediately. However, typing by "hunt-and-peck" limits entry speed. By pre-training the layout and reducing "hunt-and-peck" time, does passive tactile training give users a performance advantage on a multi-row "spatial" typing task with labels present? Beyond learning *how to type* each letter on a keyboard layout, in text entry *speed* is a key to performance. **Can tactile training improve typing speed** over time? Such questions have not been examined in previous work, but if these goals are feasible, I aim to provide data to enable others to apply this method to improve performance on other tasks that require practice.

Haptic Interface Challenges

Most keyboards have multiple rows of buttons, and each finger needs to move to control multiple keys. I hypothesize that users can learn spatial actions (movements) passively, as long as the haptic interface can convey these actions to the user. To do this, an unobtrusive wearable interface must be designed that provides this instructional stimuli. In this work, I present one such system implementation.

5.1 Motivation

Learning text input systems is challenging, and teaching techniques rely largely on repetitive typing practice that frustrates learners [13, 143]. More efficient layouts and keyboards may exist, but they often rely on the same laborious learning techniques. For example, a high school typing class may require 40-60 hours of QWERTY transcription practice and expect highly performing students to reach speeds of 40 word per minute (WPM) [58, 115]. As another example, stenotype students must spend years practicing to achieve the 180 WPM required for courtroom reporting, and over 85% of courtroom reporting students will not complete their training [57, 66]. Once a system of typing is learned, users are also reticent to learn other typing systems, inspiring work on creating partially optimized layouts that resemble the familiar QWERTY [7, 94]. Most typists will never learn DVORAK even though they may believe it is faster than QWERTY [114]. I seek to lower these barriers through passive haptic training.

Current techniques for learning the desktop or similar keyboards are often limited to active practice. Conventionally, users wishing to improve their skill perform typing drills or games [13, 143]. This repetitive practice of a motor skill is the state-of-the art to achieve automaticity [127]. Research has been done on the learning curve that characterizes this learning process for QWERTY [28, 89] and other keyboards [23, 87, 96], and even cognitive models have been developed to simulate it [28, 35]. Text entry learning is a well-defined problem [23, 87, 96]. Many "crutches" exist, such as auto-complete and search suggestions, to boost interaction performance despite these learning challenges. Research on interventions for improving keyboard learning is mostly limited to tutoring software and teaching structures in schools [13, 21, 115, 116, 142]. Other research suggests different keyboard layouts, but with the same laborious learning methods [87, 96].

Most text entry research in haptics focuses on tactile *feedback* (such as a vibration each time a key is tapped) to benefit in-situ typing performance as opposed to impact learning [11, 76]. Other haptics research uses haptic *cues or guidance* during motor tasks like typing [80, 84, 129]. Since these cues are presented during task performance though, they may only serve to be a crutch to participants and have demonstrated mixed results on facilitating learning and performance. In addition, most research on haptic training focuses on accuracy metrics, and improvement on task performance speed is largely uninvestigated [150].

5.2 Apparatus

This section details the wearable computing system and stimuli that were designed to provide passive haptic training for these studies. Design decisions made within these apparatus sections can be used as design guidelines for future projects applying passive haptic training.

Wearable device

In these studies, a single right-hand glove with embedded vibration motors is used to provide instructional tactile stimuli (Figure 5.1). The glove is fingerless for improved fit on a variety of hand sizes. A small, coin-shaped vibration motor (Precision Microdrives 310-113) is attached to **the top and bottom** of each finger and these are driven by a small circuit board. See Figure 5.2. These eccentric rotating mass (ERM) motors are driven with 3V DC

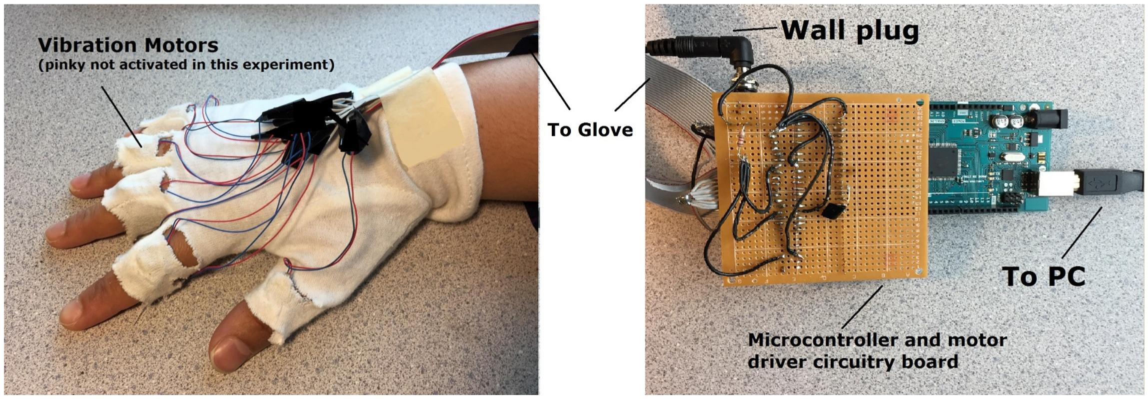


Figure 5.1: The wearable computing glove used to provide haptic training.

to provide the constant current required for peak recommended vibration strength (1.38 g) and a 200 Hz vibration frequency. The motors are driven by TI ULN2003 Darlington array chips to provide the necessary current and buffer the system's microcontroller.

Teaching Structure

We aim to teach the layout of a 10-key keypad and then improve user typing performance. The layout of the keypad is 3 x 3 with one key below the third row. I will divide the keypad into parts and train users incrementally, one row at a time. During each passive learning period, users passively "learn" one row of the randomized keypad layout shown in Figure 5.3. Teaching a row at a time allows for "chunking" [119] and infers an already-present spatial grouping both of which benefit spatial memory and may make learning easier.

To improve their performance in the second study of this chapter, I will repeat the stimuli identically in two follow-up visits. This study is a simple preliminary test of whether identical training after initial learning will result in continued performance improvements.

Stimuli

Learning periods are 15 minutes long. The middle row is taught during the first period, then the top row, and then the bottom row and thumb key (key 9 in Figure 5.3) in the last period. Each number in the row is spoken (using a previously recorded text-to-speech

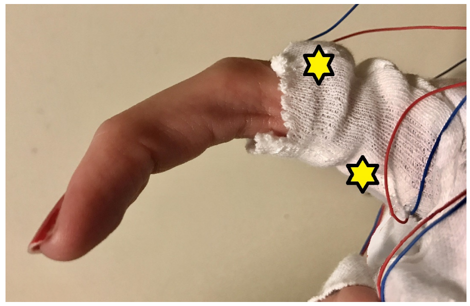


Figure 5.2: The top and bottom vibration motor locations. Stars highlight these locations on the example finger.

voice). Immediately after a number is spoken, a vibration "taps" the correct finger used to type that number key. Vibrations are about 500 ms in duration, with a 100 ms pause before the next number. There are seven second pauses between repetitions of the row, resulting in about 80 repetitions.

Here I train users on not only what finger types each key, but also whether that finger should move up to type the upper row or down to type the bottom row. I hypothesize that training of movements or "spatial tasks" is possible as long as the tactile interface can convey this to the user. Therefore, here I present one way to convey this movement using tactile taps. For keys in the upper row, the motor on the top of that finger vibrates. Similarly, for keys in the bottom row, motors on the bottom of the fingers vibrate. If a key is in the middle row, both motors vibrate. The large key on the bottom of the keypad (here labeled 6) is operated by the thumb and taught along with the bottom row. The pinky finger is not needed for typing on this keypad and is therefore not stimulated.

5.3 Study 1: Design and Methods

Twelve users (18-25 years of age, 6 male / 6 female) participated in a between-subjects study to examine entry performance on a randomized, multi-row keypad with or without passive haptic training. I hypothesize that users receiving passive training will show better performance than those without, as measured by increase in words per minute.

Figure 5.3: The keypad and randomized layout.

The reduced keyboard used here is the 4x3 number pad, which is typed in the same way as the QWERTY keyboard but uses only the right hand. The numeric keypad is the simplest commonly available keyboard where each finger controls multiple keys. It requires only one hand, reducing the amount of hardware needed for testing. Numeric data entry is a task that has been well covered in the literature making it easier to study in laboratory conditions. In addition, while not as ubiquitous as the need for QWERTY text entry, fast numeric data entry is still a required skill for many jobs, and a method of increasing learning speed could be beneficial to schools that teach those skills. Since most individuals have varying, non-negligible skill at desktop QWERTY typing I use a randomized mapping in this experiment. Unlike in previous research on passive haptic learning, the keyboard being learned here is labeled (as are most QWERTY keyboards); this labeling enables users to look for the correct key to type. To provide more information on this behavior in our study, I use an eye tracker during typing tests. Will users exposed to passive training show higher typing speeds? Can training help users learn, even on a grid-shaped keyboard where each finger must control multiple keys?

Users were randomly assigned to either the passive haptic training or control condition. Each user visited the lab for one session with the structure in Table 5.4.

PHL	Control
Pretest	
Distraction task and passive stimuli (15 min) top row	Distraction task (15 min)
Test 1	
Distraction task and passive stimuli (15 min) mid. row	Distraction task (15 min)
Test 2	
Distraction task and passive stimuli (15 min) bot. row	Distraction task (15 min)
Test 3	

Figure 5.4: Session structure. All users have the same tests and same distraction task.

Conditions

Under the experimental condition (Passive Haptic Learning (PHL)), participants receive instructional haptic stimulation (details in Apparatus section) in the background while focusing on their distraction task. In the control condition (Control), participants receive no training. All participants have access to key labels during testing.

Measures

Typing Tests

Tests gauge users' typing performance on the randomized keypad. They are given a pre-test at the beginning of the session and a test after each distraction task period (when users in the PHL condition passively "learn"). During all tests, users sit at a desktop computer and type on the keypad with the right hand (Figure 5.5). They are asked to type whatever prompts appear onscreen. The prompt corpus for each test is five randomized strings containing all numbers on the keypad (0-9), presented in 5-character halves. Proper hand position is enforced by the study observers in both studies: participants must use the correct finger to type each key. They are told to use the index finger for the leftmost keys, middle finger for

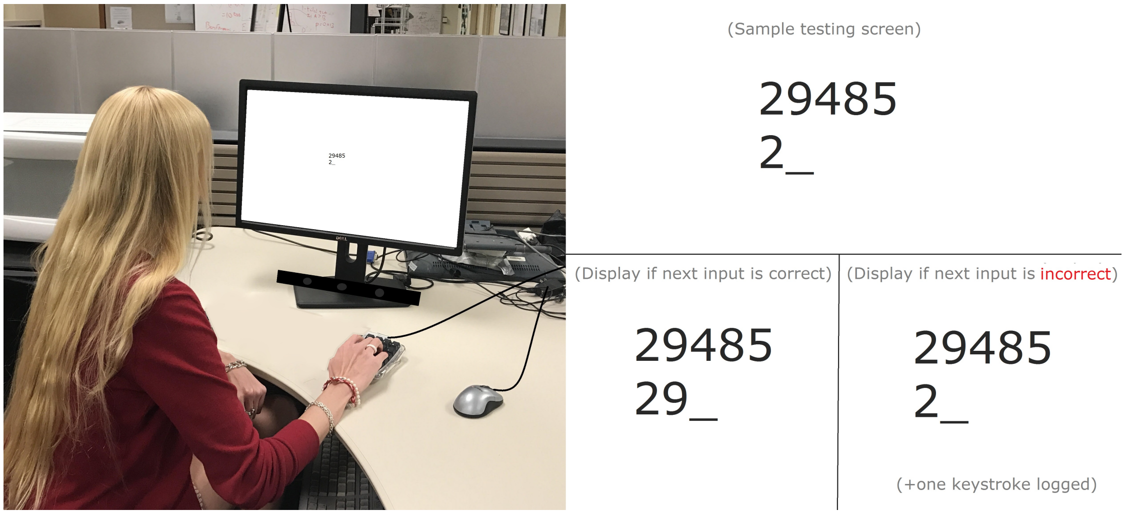


Figure 5.5: The setup for testing sessions.

the middle row, ring finger for the rightmost keys, and the thumb for the long bottom key. All participants (including control) are observed and corrected if they deviate from proper hand position. Error correction is not permitted, but successful entry of each character is required to move forward. If an incorrect character is entered, nothing new appears on screen but the keystroke is logged. This technique allows us to focus on speed. We use a Tobii EyeX eye tracker to monitor when participants are looking at the keyboard. To allow natural looking behaviors to emerge, participants are only told that the goal is to look less at the number pad and type with good skill.

Bonus test – keypad obscured For four participants (2 PHL, 2 control), we included a additional test at the end of the session. This test had the same structure and content as the others, but the participant's hand and the keypad was covered by a paper screen. This test was intended to reveal differences in knowledge of the keyboard layout.

Distraction Task Periods

The primary task from Chapter 3 [120] was used to occupy participants during the distraction period. During the 15-minute distraction tasks, users sit at a desktop computer and focus on the game (Figure 5.6). **All users are asked to pay attention only to the game**

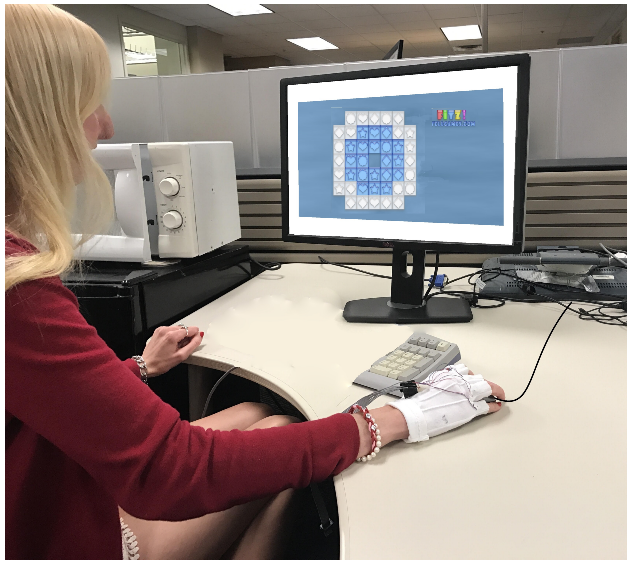


Figure 5.6: The apparatus used in the distraction tasks. (Game image on screen was digitally enhanced for this photo)

and focus on getting a high score. Users in the passive haptic learning condition also wear the computerized glove and earbuds during this time which provides the stimuli to passively "teach" them. They are told that this stimuli is related to their typing tests, but again to pay attention only to the game.

5.4 Results

Typing test software logged user responses, timing and eye tracker data. Errors, counted as extra keystrokes per character (KSPC), remain consistent for each user throughout the session and similar between groups (between Means=1.2-1.3 KSPC, SE=.08-.1 for each PHL group test; Means=1.1-1.2 KSPC, SE=.03-0.1 for control users (repeated measures ANOVA: $F = 4.6$, $p > 0.5$)). No significant difference was found in distraction task scores (unpaired t-test $t(10)=1.00$, $p=0.34$). Both groups increase their typing speeds, calculated as words per minute (WPM), from the beginning to the end of the session as shown in Figure 5.7 (PHL: M=11.4 WPM, SE=0.85 to M=15.1 WPM, SE=2.12; and Control: M=10.8 WPM, SE=1.2 to M=14.3 WPM, SE=1.8), but any difference between groups was not significant (unpaired t-test $t(10)=0.06$, $p=0.95$). Time spent looking at the keys decreases

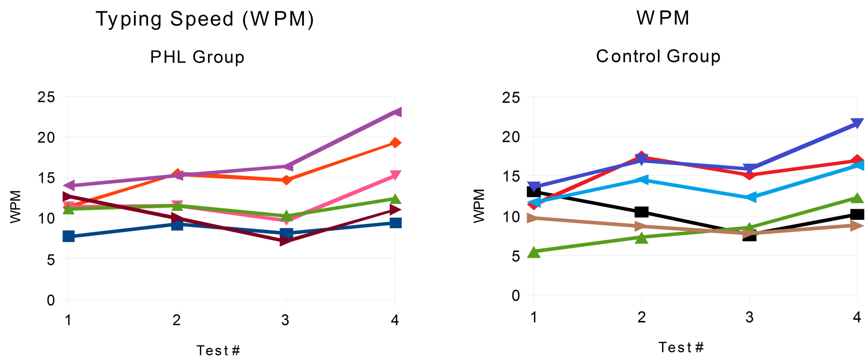


Figure 5.7: Typing speed by user group across tests in the first study. Each line is one user.

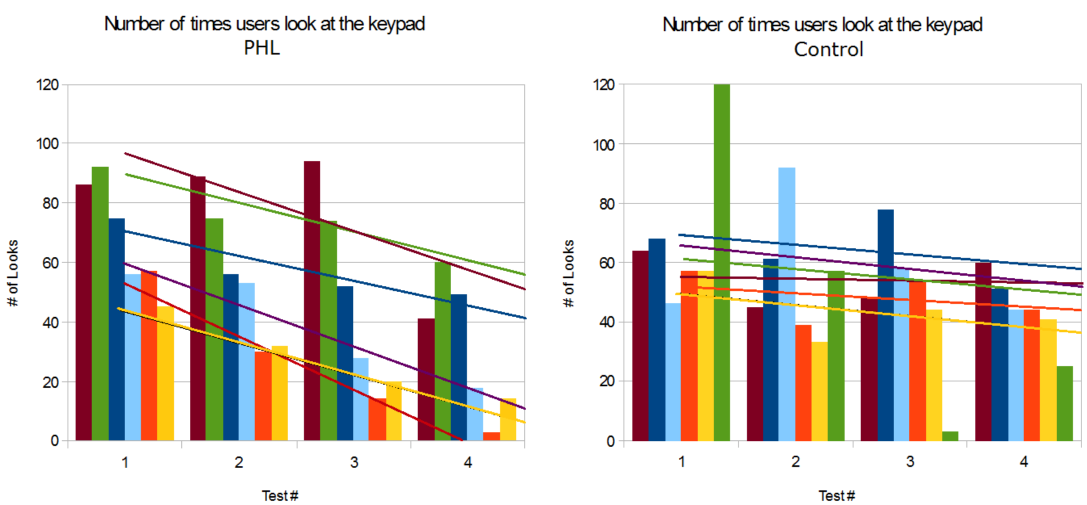


Figure 5.8: Number of looks at the keyboard for each test. Each color bar/trendline is one of the six users in that condition group.

some amount over time in both conditions. In particular, the number of looks decreases significantly for users receiving passive training (repeated measures ANOVA: $F(5, 3) = 23.23$, $p < 0.05$). On the contrary, those in the control group show no significant reduction in looks at the keyboard (repeated measures ANOVA: $F(5, 3) = 1.297$, $p > 0.05$). See Figure 5.8. When the keyboard was obscured for the bonus test, the two users in the PHL group demonstrated consistent error rates with their uncovered performance (increase M=0.022 KSPC). The two users in the control group, however, showed an increase in error when they could not look at the keys (increase M=0.45 KSPC). This difference is shown in Figure 5.9.

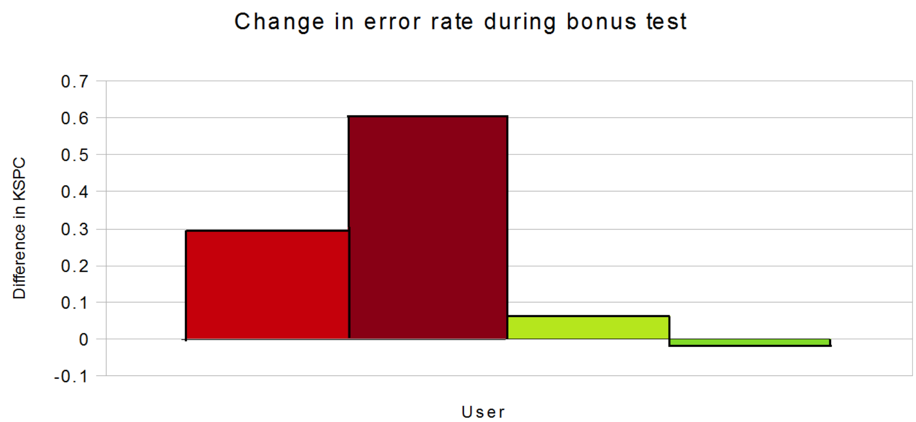


Figure 5.9: Average increase in errors per character in the bonus test of the pilot study. PHL group users are in green (right) and control group users are in red (left).

5.5 Discussion

Results suggest that passive haptic training has an effect on learning this task. It was unknown whether a skill involving multiple keys controlled (movements) by each finger could be conveyed using the tactile interface, but differences in metrics between groups seem to indicate that **the haptic interface conveyed this spatial task.** Error remained low for all participants, likely because the keyboard layout was labeled. Those receiving passive haptic training **looked at the keyboard less** than those in the control group; suggesting that PHL users had more certainty in their internal knowledge of the layout. Results of the few trials at the "bonus test" also indicate this trend; when control group users could no longer reference the layout visually, they doubled or tripled their error. PHL users, however, showed no increase in error when they could not see the keyboard – suggesting that these users know the layout. These results indicate that passive haptic training may help users pick up this skill more quickly and encourage further research on passive haptic training for keyboard typing. Although differences in speed between groups were not significant after this single session, results on learning were encouraging. It is possible that speed differences may emerge after users have practiced the skill for longer, so I next conduct a lengthened version of this study to examine for longitudinal trends in keyboard typing performance with passive haptic training.

5.6 Study 2: Design and Methods

I next conducted a multi-session study to examine for speed differences in non-novice users. Can passive haptic training help users become faster at a skill in less time? I hypothesized that after three sessions, users exposed to passive training will demonstrate faster typing speeds than those in the control group. I recruited 14 participants for this between-subjects study (18-24, 6 Male / 8 Female) and randomly assigned each to either the passive haptic learning (PHL) or control condition.

This study consists of three sessions, 5-24 hrs apart. Each session is identical to the structure used in the first study, except all sessions here include the bonus test at the end.

5.7 Results

Typing and eye tracker data were logged by the testing software. Errors (keystrokes per character (KSPC)) remain consistent and low during tests other than the bonus test throughout all sessions. No significant difference was found in distraction task scores between groups (unpaired t-test $t(10)=0.6926$, $p=0.51$). Change in typing speed was evaluated as difference in words per minute (WPM) from the initial pre-test to the last "test 3." Users exposed to passive training showed a significantly greater increase in their typing speed: 11 WPM faster on average versus 2.2 WPM for control (PHL SE=2.1 WPM; control SE=1.5 WPM; unpaired t-test $t(12)=3.32$, $p=0.0061$). Figure 5.10 shows this trend.

The speed differences found between groups are also found in the trends across all tests (repeated measures ANOVA for a difference in trend between groups: $F(12, 11)=22.06$ $p < 0.0001$).

I also evaluated the number of times that users choose to look at the keyboard during each typing test. Both groups look at the keyboard about the same number of times at the start of the study (M=71, SE=7.2 for PHL vs M=77, SE=10.2 for control) per test, but by

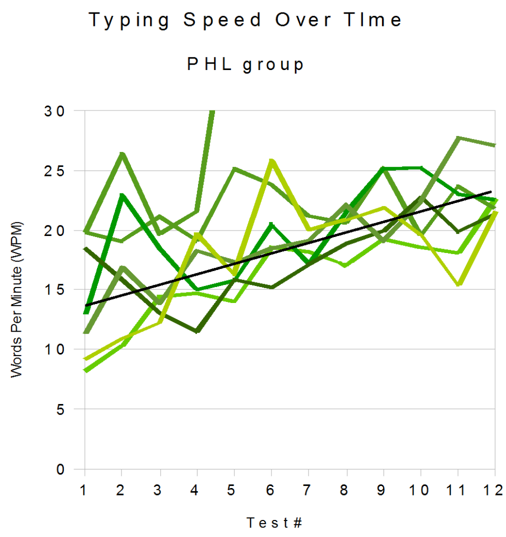


Figure 5.10: Typing speed on each test including group trendlines. Each line corresponds to a user, showing changes in speed over time. One line is truncated for scale (PHL user reaches above 30 WPM at session five and remains above this pace).

the end of session one, PHL users significantly reduced their average number of looks per test (M=42). Number of looks per test was compared between the beginning and end of the study. Users exposed to PHL reduced their looking at the keyboard significantly more than the control group (unpaired t-test $t(12)=2.56$, $p=0.0246$) ending at M=31, SE=7.4 for PHL vs M=48, SE=8.2 for control for the last test.

Control group users showed higher error during the bonus tests. On the bonus test at the end of session one, the difference is most apparent: Control users showed an average increase of 1.26 KSPC (SE=0.71). PHL users had a negligible -0.011 KSPC average change in error when the keyboard was obscured (SE=0.0037). The difference was not quite statistically significant due to variance in control user #1 (unpaired t-test $t(12)=1.84$, $p=0.09$).

5.8 Discussion

Results in the longitudinal study are consistent with those of the first study and also expose new trends. After the first session, where most change occurs, more differences in typing

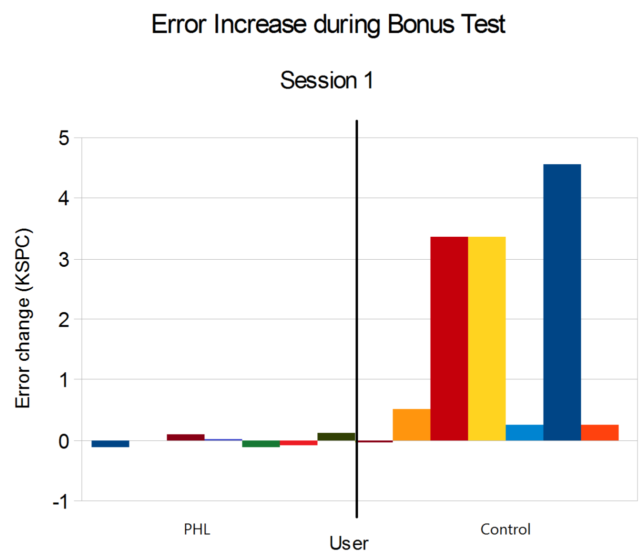


Figure 5.11: Increase in error when users could not look at the keyboard. Bars left of the line represent error scores for users in the PHL group, bars right of the line are control group users.

performance between groups become apparent.

Data from this study indicate that passive training has positive effects on learning metrics, congruent with differences found in study one. Error remains consistent and low throughout all sessions in this study, likely because of the labeled keyboard layout. **PHL group users once again look significantly less at the keyboard as time goes on.** Control group users maintain the same level of glances at the layout. These results indicate that those exposed to passive training feel less need to reference the labels, suggesting that they know the layout better. Looks from PHL participants are also more searching/orienting in nature (longer average looking duration), whereas the control group is observed to rely on many quick glances throughout the study. The bonus test results also suggest a difference in knowledge between groups. When control group users were not permitted to look at the keyboard during the bonus tests, most demonstrated large increases in error. Consistent with the pilot results of this test during study one, PHL users showed negligible change in performance when they could not see the keyboard. These results suggest that those exposed to passive training are more familiar with the layout. This difference between groups was greatest during session one. The control group improved some on the bonus test in session two and three, likely due to gradual learning of the layout through practice; however, the PHL group continues to out-perform the control group on other metrics (such as speed) during these sessions. Does this suggest that performance differences in sessions two and three are due to motor skill rather than just layout knowledge?

Results also indicate that PHL had an effect on typing speed. **Users who had passive instruction demonstrated statistically significant and functionally different increases in typing speed.** What does that mean for keyboard learning? I suggest that passive haptic training, facilitated by wearable computing, may be a beneficial aid to learning and improving typing skills.

5.9 Conclusions

In this chapter I conducted two experiments focused on typing on a randomized numeric keypad [121]. Half of participants were exposed to training stimuli from a wearable computing glove while they focused on other tasks. Although users in both groups had all keys labeled the entire study, users who were exposed to passive haptic training significantly out-performed the control group in speed over time. The training group reached speeds typical of touch-typing after the third session, while the control group remained in the typical desktop hunt-and-peck-method speeds (<23 WPM) [96] throughout the longitudinal study. **When users were prevented from looking at the keyboard, the training group demonstrated consistent accuracy,** while those in the control group doubled their error. These results suggest that passive tactile training enabled greater knowledge of the keyboard layout and increased typing speeds. These findings may inform research in haptic training systems for QWERTY typing, other keyboards, and the use of passive training to improve speed and performance of other tasks that require practice.

In this chapter, I once again train users on discrete actions and their associated meanings. Here, however the skill is a **spatial task** where each action may require movement. In addition to learning *how to type* each letter on a keyboard layout, *speed* is a key to performance. This work suggests that **passive training can help improve performance over time.** What's more, the numeric keypad used here had each key labeled with the corresponding symbol so that even a novice can begin typing accurately immediately. Passive training was associated with better performance **even in the presence of labels that provide all information needed to perform a skill accurately.** In the next chapter, I examine training for a rhythmic skill.

CHAPTER 6
CONVEYING RHYTHM

In prior work, tactile stimuli were used to teach piano. However, rhythm was not shown to be taught. Many applications may want to convey rhythm during passive learning or may want to use time-differentiated cues to expand the bandwidth for haptic interfaces. In this chapter, I present two studies of teaching temporal patterns through passive stimulation. To demonstrate this I teach the Morse code text entry system – a system that is not only still in use by the Air Force and Navy, but is also considered one of the top 10 assistive technologies [4] and was recently integrated into all Android phones for this purpose. I hypothesize that temporal information can be conveyed and trained using repeated passive tactile stimulation.

Passive Learning Challenges

Here, I examine Morse code, a very different text entry system from Braille. Again, this work aims to train discrete groups of actions and their meanings. However, this entry method is rhythm-based and requires only one button to type [98]. Morse code requires a sequence of multiple "keystrokes" to produce each letter. Keystrokes in Morse are known as dots and dashes and are differentiated by duration of the key-press – dashes are by definition three times the duration of a dot. Each letter is essentially a rhythmic pattern. **Rhythm has previously not been successfully trained passively.** Furthermore, I use off-the-shelf hardware to apply the stimuli to different body parts (head and wrist), while users are tested on their knowledge of the system and performance using their hands. Therefore, participants must extract meaning from the tactile training, rather than simply reproducing the pattern they felt. In addition, it is not known how long users must receive background stimulation in order to know the information being stimulated. Previous work in passive haptic learning used standard times, such as 15 or 20 minute learning periods [125]. Could less time be sufficient? My second study touches on this question.

Haptic Interface Challenges

Previous studies required custom hardware for stimulation, but here we test if pre-existing devices can be used to provide instructional stimuli. Google Glass smartglasses and Android smartwatch are both used in separate experiments. An off-the-shelf device may allow many more users to try passive tactile learning. Here, I also describe how to create appropriate tactile sensations using the bone conduction transducer (BCT) on Google Glass In the second study, I also do a preliminary test of performance differences between two different doses of passive stimulation.

In addition, researchers have used smartwatch actuators for alerts and guidance [78], but it is not clear whether they can be used to enable haptic learning. The smartwatch's haptic element is typically a low-amplitude actuator designed for subtlety and to not drain power from the wearable [72]. In contrast, apparatuses producing stimulation for haptic learning typically include hardware to support higher amplitude stimuli or even physical manipulation [121, 146]. In addition, the forearm is a challenging area for cutaneous perception [50]. The wrist is also a bony area, which may improve vibrotactile perception [40, 52]. A few researchers have studied vibration stimulation with wrist apparatuses or smartwatches. Lee used LRA-type tactors with and without added nubs to examine information throughput on the wrist [78]. Others used smartwatches to support activities such as navigation and alerts [16, 18]. This work provides useful background; however, research has not established if smartwatches can convey a new skill or provide background haptic stimuli for passive learning. The subtle stimuli from smartwatches may not have the necessary salience, amplitude, or even be in an appropriate location on the body. Here, in the second study of this chapter, I do a preliminary test of passive haptic learning from a smartwatch.

Figure 6.1: Left: Morse codes for the letters *A*-*G*. Right: A straight key for producing Morse.

6.1 Motivation

Mobile devices such as smartwatches, Google Glass, and other wearables are becoming increasingly popular, but users report a common complaint. Users want to have a form of nonverbal (silent) text entry, ideally eyes-free, using touch [74, 134]. The slim, streamlined nature of these devices precludes many standard text entry methods though. There has been research in search of a solution - including new or optimized keyboard interfaces for smartwatches [7] and novel entry methods such as rotational text entry [95]. However, discrete text entry remains a challenge on these devices because it is hard to create an interface that a human can dexterously manipulate and is easy enough to start using such that it is not abandoned. In addition, mobile devices continue to decrease in size, and many extremely low-profile devices such as hearing aids, electronic textiles, and headsets cannot support these methods at all. Perhaps a non-visual, one-channel system like Morse code could provide some solution, but there are learning costs and barriers that prevent the adoption of any non-QWERTY text entry systems such as this.

Morse code is an essential tool in military and accessibility applications, despite the learning challenges. Air Force and Navy recruits are trained in Morse and similar cryptologic technologies still today. “Morse code continues to be an inexpensive and efficient means of communication for many states throughout the globe,” said Senior Chief Cryptologic Technician (IDW/NAC/SW/AW) Tony Gonzales in 2016. It is also commonly used

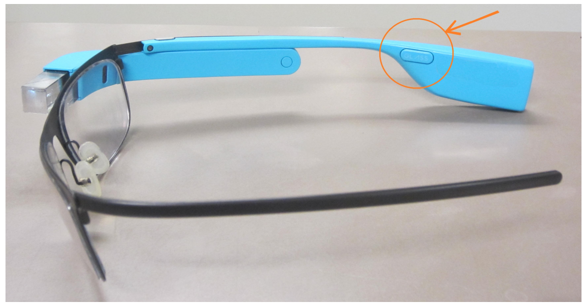


Figure 6.2: Glass's bone conduction transducer.

in commercial navigation [97]. In addition, Morse code is an accessible text entry system for individuals with motor challenges. Morse was named one of the "Top 10 Accessibility Technologies" by RESNA [4]. Android smartphones also recently added a Morse code keyboard into the accessibility settings for their devices. But learning this imput method is challenging for users. Here I explore if passive tactile stimuli can rapidly and unobtrusively train the actions used to produce each letter.

6.2 Apparatus: Google Glass

This section details the wearable computing system and stimuli for passive haptic training in this chapter's first study. **Design decisions made within these apparatus sections may be used as guidelines for future projects applying passive haptic training.**

Wearable device

Previous work used custom hardware to administer tactile stimuli for passive haptic training; however, many modern wearable devices such as smartwatches, mobile phones, and fitness trackers include actuators and could potentially be used instead. For this study, an off-the-shelf Google Glass was selected. I found that Glass can produce both tactile cues and audio feedback using its bone conduction transducer, and Glass's touchpad allows simple input of Morse code. Thus, with Glass, only one device is needed for both training and testing in the study. While smartwatches are more common and many include a vibration motor for tactile feedback to the user, the perception of tapping during passive learning might be masked by clothing touching the arm or by movement of the arm itself. So for this initial research, we use Glass which also has the benefit of not requiring an external headset for audio.

As shown in Figure 6.2, Glass relies on a bone conduction transducer (BCT) for sound output. I hypothesized that the bone conduction audio system could be transformed to a haptic element by using low-frequency audio signals. We discovered that a 15 Hz square wave sent to the BCT produced a discernible vibration against the head above the right ear. Frequencies over 30 Hz do not produce noticeable tactile feedback, and the quality of feedback seriously degrades over 20 Hz. Under 10 Hz produces a signal with clearly discernible oscillations resulting in poor differentiation between oscillations and Morse code dots. Between 14 Hz and 16 Hz was found to be the ideal range for producing tactile feedback. Peak vibration amplitude at 15 Hz was found to be 1.8 g, as measured by an accelerometer.

Teaching Structure

We aim to teach all 26 letters of the alphabet in Morse code. Each letter in Morse code requires a series of keystrokes, making learning additionally complex. I break the alphabet into parts using a pangram (sentence containing all letters of the alphabet), as was done in Chapter 3. The pangram sentence used is “the quick brown fox jumps over lazy dog.” Each part is a distinctive word, helping users remember what letters they are learning during each short training session. I use this **piecemeal structure to incrementally teach the experimental group one word at a time using repeated passive stimuli.**

Stimuli

Google Glass “taps” on the posterior right skull of participants using the BCT in the smart-glasses’ temple. Each letter of the alphabet in Morse code is represented by a series of dots

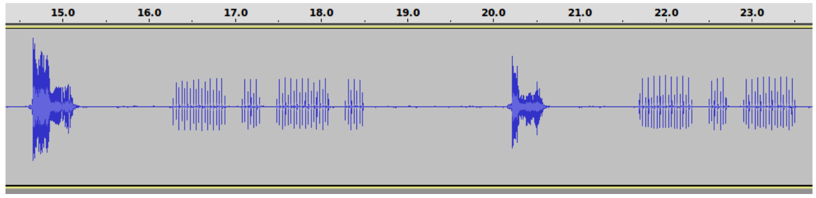


Figure 6.3: Activation profile for haptic stimuli produced by Glass. Taken using a microphone, this signal shows the letters *C* and *K* spoken, each followed by vibrations indicating their equivalent Morse code (-.-. and -.-).

and dashes and is entered using a keying machine (see Figure 6.1). The dots and dashes in Morse code are short or long taps on the key (by definition, a dash is three times the duration of a dot). **I translate this rhythmic system into haptic cues, making each letter a tactile "rhythm."** Dots and dashes are differentiated by their duration. We assumed that the maximum input speed a novice might reach during our study is 10 words per minute. At that speed dots are expected to be less than 200 ms and dashes are greater than 400 ms. After some informal experimentation, we programmed Glass to represent dots as 200 ms pulses at 15 Hz vibration, and we set dashes as 600 ms in length.

Stimulation for the word being taught is repeated approximately 25 times (depending on length of the word) during the 20 minute learning periods. Audio for the word is presented 2 seconds before each repetition and the word is spelled as audio for each letter precedes by one second (not overlaps), the dots and dashes (tactile rhythm) representing that letter. There is a 150 ms pause between all dots and dashes, and a 1.5 second pause between letters and a 10 second pause between repetitions.

6.3 Study 1: Design and Methods

I recruited 12 participants (7 male, 5 female; 18-25 years old) for a between-subjects study and randomly assigned each participant to either the passive haptic learning (PHL) or control condition. I hypothesized that passive, instructional stimulation can reduce errors on Morse code post-tests, measured using a Dynamic Time Warp algorithm. Our passive train-

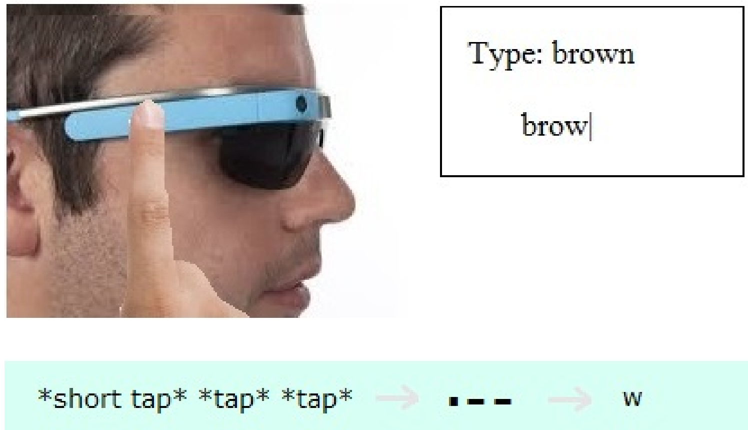


Figure 6.4: Left: User tapping Google Glass's touchpad, which runs most of the length of the electronics pod. Right: Example screenshot of Glass's display during input tests. Bottom: The user has just tapped Morse code for the letter *W*.

ing system breaks the alphabet into eight parts and teaches one part at a time. Therefore, this study contains four visits and each visit is divided in half – making eight sessions which each focus on one part of the alphabet (one word). Here, we use the pangram "the quick brown fox jumps over lazy dog" to divide the alphabet. By passively introducing one word (several letters of the alphabet) at a time, we teach incrementally. The structure of each session is as follows:

- Testing: word 1
- Distraction task and training condition (30 min.): word 1
- Testing: word 1, word 2
- Distraction task and training condition (30 min.): word 2
- Testing: word 2

Conditions

Under the experimental condition (Passive Haptic Learning (PHL)), participants receive haptic stimulation (details in Apparatus section) to teach a word in Morse in the background

Structure and Test Content

session start

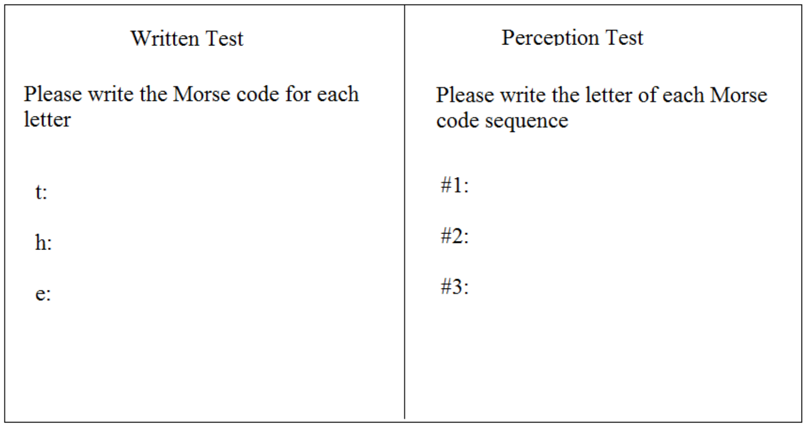
	Session 1	Session 2	Session 3	Session 4
Input Pre-Test	the quick pangram1 x 1	brown fox pangram1 x 1	jumps over pangram1 x 1	lazy dog pangram1 x 1
Distraction Task + Stim	the	brown	jumps	lazy
Written Test	t, h, e	b, r, o, w, n	j, u, m, p, s	l, a, z, y
Input Test	pangram1 x3 the x3 t, h, e (randomized) x3	pangram1 x3 brown x3 b, r, o, w, n (at rand.) x3	pangram1 x3 jumps x3 j, u, m, p, s (at rand.) x3	pangram1 x3 lazy x3 l, a, z, y (at rand.) x3
Perception Test	h, t, e	n, r, o, b, w	u, s, j, m, p	a, y, z, l
Distraction Task + Stim	quick	fox	over	dog
Written Test	q, u, l, c, k	f, o, x	o, v, e, r	d, o, g
Input Test	pangram1 x3 quick x3 pangram2 x3 q, u, l, c, k (at rand.) x3	pangram1 x3 fox x3 pangram2 x3 f, o, x (at rand.) x3	pangram1 x3 over x3 pangram2 x3 o, v, e, r (at rand.) x3	pangram1 x3 dog x3 pangram2 x3 d, o, g (at rand.) x3
Perception Test	u, c, i, k, q	o, f, x	v, e, o, r	g, o, d
			Final Written Test	a-z
			Final Perception Test	a-z (at random)

Figure 6.5: Session orders and test content. The written test and input test rows demonstrate what users were prompted to write/enter (to test production of Morse code). The perception test row is what was presented to users through vibrations (to test recognition of Morse code).

while focusing on their distraction task. In the control condition (Control), participants wear Glass but only hear audio of the word repeated.

Measures

Users have a test of Morse code before and after every distraction task. At the beginning of the study, I give participants a Morse code "input test" on all letters to gauge their baseline level of knowledge. This full test is repeated at the end of visit four. All sessions start with an "input test" (pre-test) of the current word. Following each distraction task, participants complete two tests on Morse code production ("written test" and "input test"), and test of Morse code recognition ("perception test"). Tests are described in detail below (see Figure 6.5).



Written Test

Please write the Morse code for each letter

t:

h:

e:

Perception Test

Please write the letter of each Morse code sequence

#1:

#2:

#3:

Figure 6.6: Examples of written and haptic perception test papers.

Written Test

This test presents participants with a list of letters from the word which they were just exposed to and asks them to write the Morse code (dots and dashes) for that letter (see Figure 6.6). **This medium most clearly reflects *their knowledge* of Morse because they do not have to enter Morse code using an unfamiliar method (like tapping).** The test is given immediately after the distraction task so that the participant's knowledge is not augmented by any active learning that occurs during the input test (which gives the participants visual feedback). Users are told to answer what they know, and if they are totally unsure, they should answer with a question mark. At the end of their final (fourth) session, users are also given a written test on the full alphabet. Test content for each session is detailed in Figure 6.5.

Sensing Morse Input on Glass's Touchpad

Users tap on the Glass touchpad to enter Morse code during input tests. To enable typing on Glass, my students built an activity to receive user input and administer tests. Users wear the Glass normally and are able to type on the device touchpad by tapping with their index finger (see Figure 6.4). Glass's touchpad (Figure 6.4) runs most of the length of its electronics pod along the right temple and can sense multiple simultaneous touches. While Glass's multitouch trackpad could allow iambic keying of Morse code, I chose to emulate the more familiar straight-key [98] which is used by simply tapping with one finger.

In Morse code, a quick tap is a dot and a dash is a longer touch. Thus, we chose to interpret taps of 300 ms or less as dots and those of greater than 300 ms as dashes. We decided to use this set threshold rather than have a rolling average threshold that may cause recognition errors by the system and confuse participants with inconsistencies. To leave time for a user to think about the dots and dashes that comprise each letter, the system waits for 1200 ms of inactivity before committing and **displaying the resulting letter (providing some feedback on Morse to the user).** I chose this threshold to reflect the speed that I thought a novice may reach after passive training: approximately 10 WPM. At this speed, dots are expected to be less than 200ms and dashes are greater than 400ms, so we chose the cutoff duration of a touch meaning a dot to be 300ms. These choices still seem adequate in retrospect after the study.

Input Test

Users tap Morse code on Glass's touchpad during the input tests. Because participants must enter answers on the touchpad, **the input test reflects both learning of Morse and their skill at tapping Morse code on Glass.** Audio prompts (along with visual prompts) tell users what letter to type during input tests (see Figure 6.4). No corrections are permitted (e.g., backspace). We chose to provide users with visual feedback of each letter they type instead of obscuring this information. While this feedback facilitates some active learning during the testing periods, we aim to create conditions conducive to learning (see Figure 6.4). In addition, if we released this project into the market as an application for Glass or for a smartwatch, we would attempt to aid learning in every way possible. Thus, for ecological validity, we decided visual feedback was appropriate.

Test content is detailed in Figure 6.5. Input tests after distraction tasks include three tries at typing a second pangram: "when zombies arrive quickly fax judge pat." This second pangram is included to judge how well participants use their knowledge as opposed to simply learning a set sequence.

Perception Test

Referred to as "coding" in Morse code [98], we also test perception and recognition of Morse signals. The final of the three tests, the perception test is also paper-based and asks users to attend to a series of Morse code vibrations and write down the letters they recognize (see Figure 6.6). This Morse code is administered at a rate of 10 wpm by Glass and contains only the letters from the word to which the participants were just exposed. Letters are presented in a random order and only played once. Users can pause the system between letters, but many choose not to. The final session of the study concludes with a perception test of all letters in the alphabet in random order.

Distraction Task

Each session contains a 20-minute distraction task. During the distraction task:

- All users wear Glass
- Control group users hear Glass repeatedly spell a word via audio (no Morse code information)
- PHL users hear Glass repeatedly spell a word via audio and feel the Morse code of each letter tapped on their heads

Participants are told to focus exclusively on the game and achieving a high score and not to pay attention to any stimuli from Glass. The scored primary distraction task, Fritz!, was selected based upon its sensitivity as a metric for distraction and is used starting in Chapter 3 to gauge a user's ability to focus even while receiving passive stimulation [120].

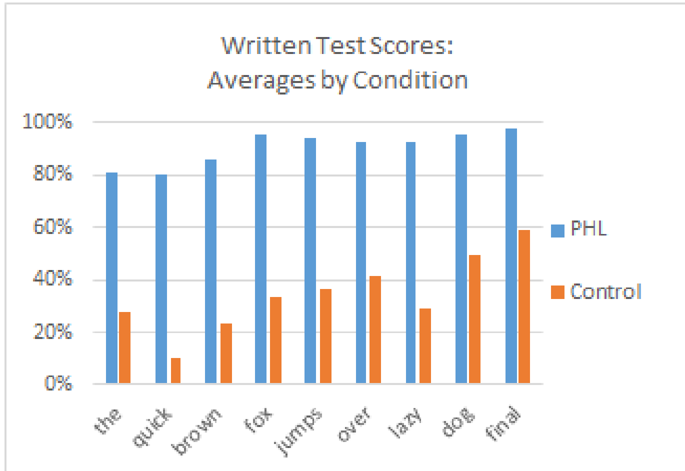


Figure 6.7: Average score by condition on each written test. "Final" refers to the test of the full alphabet at the end of session 4.

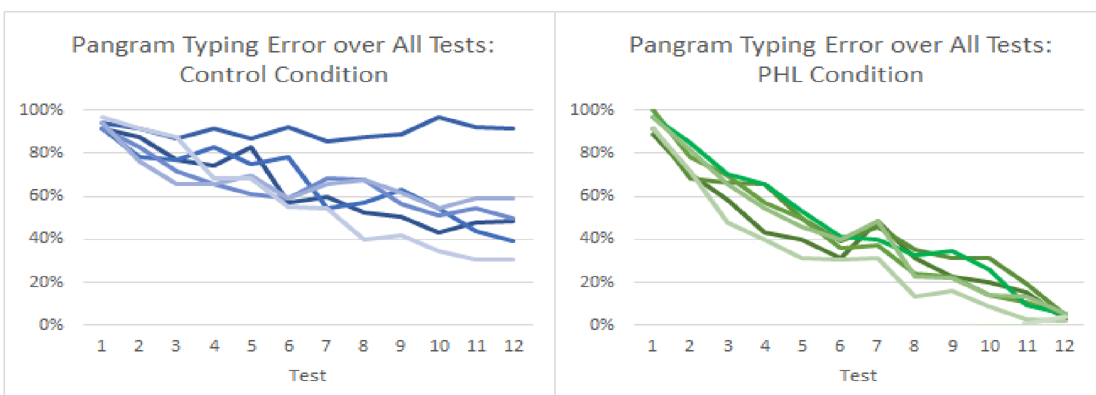


Figure 6.8: Typing error rates for the full alphabet ("the quick..." pangram) on each input test. Each line represents a user's performance over time.

6.4 Results

Significant performance differences were found between conditions, with those receiving passive training performing better than those in the control group [125]. Performance on the distraction task (Fritz game) showed no significant difference between groups ($t(10) = 0.424$, $p=0.372$).

Written Test

For the paper-based written test, I analyzed what letters participants correctly answered in Morse. The number of correct letters out of possible letters in the word formed a percentage score for each word's test. I compared the performance of users in the PHL group versus those in the control group and found significant differences. T-tests reveal that PHL users performed significantly better than control users on all written tests. Mean scores for the PHL group ranged from 80-100% for all tests (versus 0-50% for the control group) as shown in Figure 6.7. On the final test of all letters in the alphabet, PHL users scored a mean percentage of 98.0% correct answers (SE=0.015), whereas control group users scored 59.0% on average (SE=0.102). This difference was again significant ($t(10)=3.917$, $p<0.0013$).

Input Test

Accuracy on the input tests was calculated using a Mean String Distance algorithm and used in the Total (Uncorrected) Error Rate metric standard in text entry evaluation [89]. We used these measures to compare the letters that users entered with the prompted string of letters (ground-truth).

To analyze the performance of users over time, we examined error rates on the pangram over the four sessions. The pangram reflects participants' knowledge of all letters in the alphabet (in Morse) and their ability to type them on Glass. I examine the single attempt at

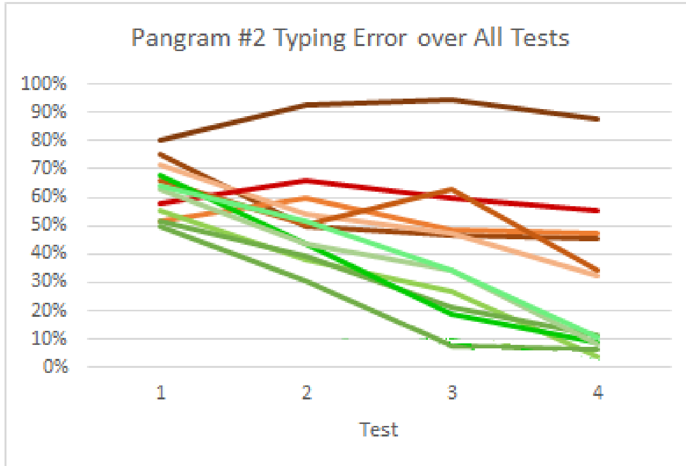


Figure 6.9: Typing error rates for the full alphabet "when zombies attack" pangram over all four attempts. Each line represents an individual user's typing performance over time. Red lines are users in the control group, and green lines are users in the PHL group.

typing the pangram given during each pretest and the average of the three trials given during each test. Users who receive passive haptic training demonstrate different trends in performance over time – with all PHL users reaching lower error scores than all control group users after the first session. We graph these results in Figure 6.8. A single-factor ANOVA reveals that passive training has a significant effect on performance (F=54.3, $p<10^{-9}$).

Starting error levels were not significantly different between the groups, but all PHL users finished the sessions with less than 6% error on their final test of the full alphabet (the pangram), whereas the control group finished with a mean error of over 53%.

I also examined error rates when typing the second "zombies" pangram. This result demonstrates users' knowledge and input performance on all letters of the alphabet in a different order than they have been taught. I average the three attempts users are given at typing this pangram during the end of each session (see Figure 6.9). A single-factor ANOVA reveals that passive training has a significant effect on performance here as well (F=17.4, $p<0.0003$). Users receiving passive instruction finished with a group average of 7.3% error on their last test (SE=0.013), while the control group had 50.5% mean error (SE=0.082).

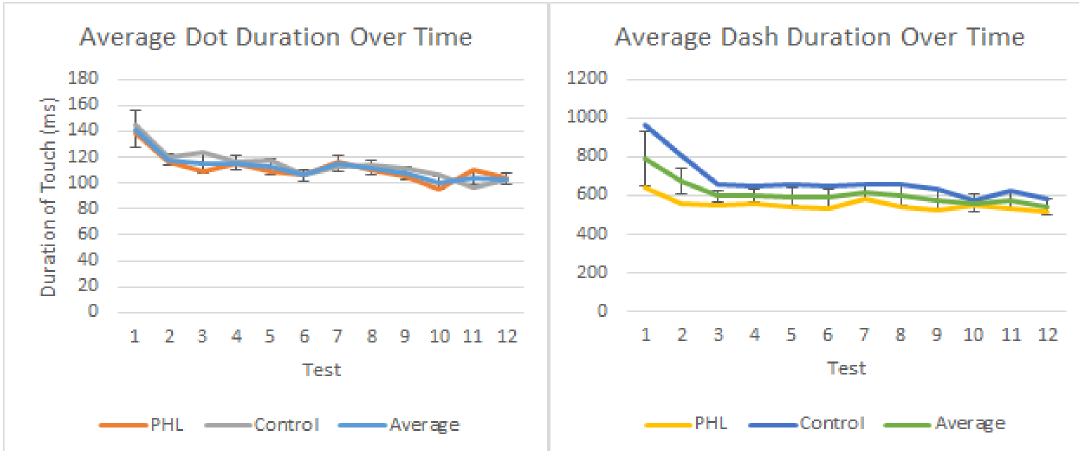


Figure 6.10: Average dot and dash touch durations over all tests. Standard Error bars are shown on average lines.

Participants progressed from initial speeds below 2.5 wpm to nearly 4 wpm when typing the pangram. However, these numbers can be misleading. The system "commit" wait time in this experiment, intended to allow novice learners time to think when inputting the components of each letter, causes reduced speeds. Calculating speeds without the sum of these 1200 ms system pauses shows average entry rates in excess of 8 wpm in the PHL group, which is close to our targeted maximum entry rate of 10 wpm.

Figure 6.10 shows the shortening of the average duration of a dot and dash over the course of the study. Average dot durations were initially 141.5 ms before converging to 103.1 ms by the final test (SE1=14.5; SE12=4.55). Dash durations began with more variance and a mean duration of 793.8 ms, eventually converging to 543.8 ms (SE1=140.8; SE12=42.4). The 300 ms threshold distinction between dot and dash duration chosen at the beginning of the study continued to be adequate throughout the study. It would be interesting to examine if a lower cutoff time forces faster typing speeds from users in order to comply with the system.

The difference in typing errors in each word, before and after intervention, was also examined. Users are given one attempt at typing the session's two words during the pretest; after the distraction task (learning period) for that word, users are given three attempts at

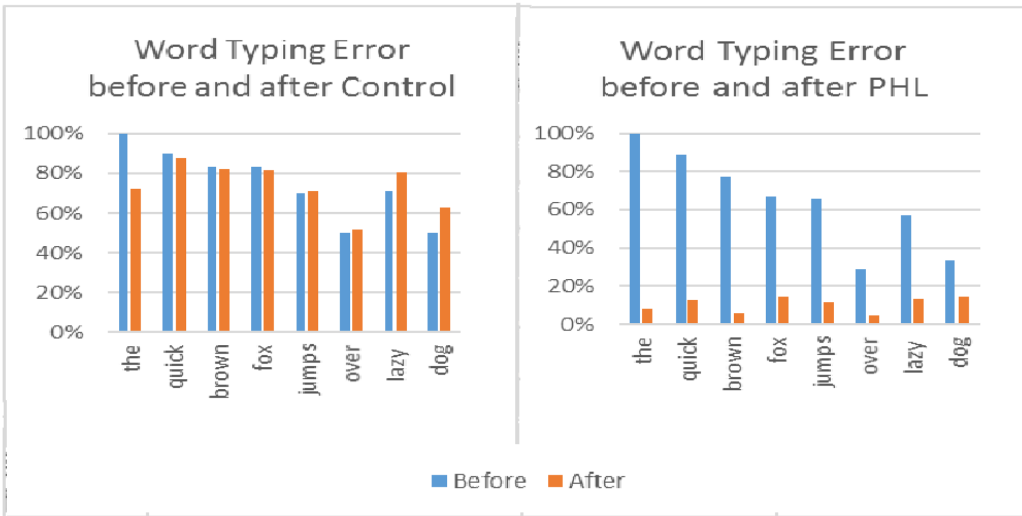


Figure 6.11: Typing error rate on each word before and after intervention.

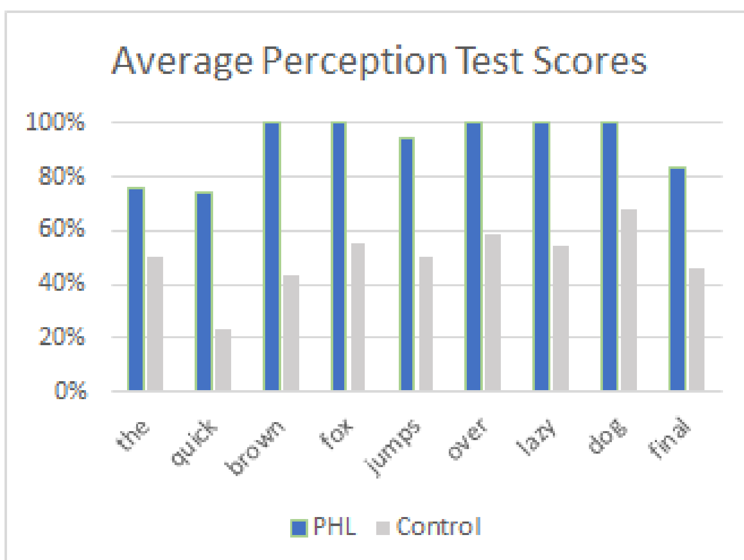


Figure 6.12: Average score by condition on each perception test. “Final” refers to the test of the full alphabet at the end of visit four.

typing the word during the input test. We compared this first trial with the average of the three post-intervention attempts and found significant improvements after passive training for all tests. As the left graph of Figure 6.11 illustrates, there was no significant difference in control group performance (t-test: t(7)=0.226, p=0.414). There was a significant accuracy difference after users received PHL (t-test: t(7)=6.06, p<0.001). Mean performance changes between the groups show a difference that was statistically significant for all words after Bonferroni correction (t-tests, alpha=0.05/8).

Perception Test

Users in the PHL group also performed better on the perception tests. When we analyzed the number of letters that subjects correctly recognized (forming an error score like that of the written test), users in the passive training group scored over 90% on six of the eight word tests. Users in the control group had mean scores all between 20-68%. This result is illustrated in Figure 6.12, and t-tests show that there was a significant performance difference between the groups. On the final test of the full alphabet, PHL users were able to correctly recognize 83.3% of all letters presented in Morse code (SE=0.041), while control group users recognize 46.1% (SE=0.076) correctly. T-tests indicate a statistically significant difference in the means between the two groups (t(10)=4.31, p<0.0008).

6.5 Discussion

Results suggest that passive stimulation augmented learning of Morse code. This work demonstrates passive tactile training of a rhythm-based system. Each dot or dash stimuli is differentiated not by location on the body but solely by difference in duration.

This work is not teaching a motor skill passively, but rather directly teaching a system of meaning through passive stimulation. The area stimulated (the head) is not the body part used to perform the skill (hands tapping Morse). I also use an existing wearable device for passive haptic training and generate tactile sensation using a bone conduction transducer.

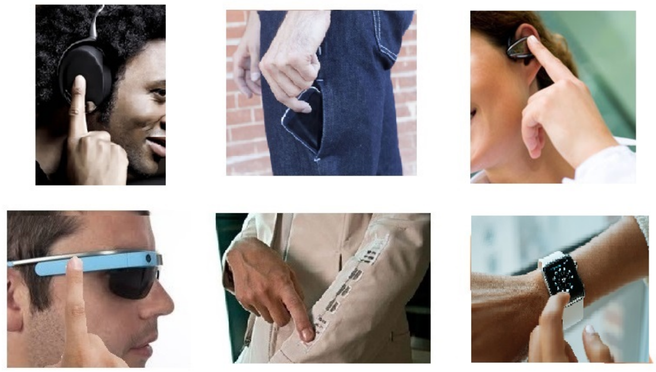


Figure 6.13: Mobile devices such as earphones, cellular phones, Bluetooth headsets, head-up displays, electronic textiles, and smartwatches may benefit from a silent, eyes-free, small profile text input system such as Morse.

Written test results show significantly better, nearly error-free performance by those who received passive training, suggesting that the passive instruction helped increase users' knowledge of the entry system.

Input tests indicate learning and reduction of entry errors over time, and results suggest that passive tactile training also helps users reduce errors more rapidly with little additional active learning or practice. Some active practice occurs during the input tests as we anticipated (when users are provided with visual feedback for the letters they type), which results in some learning over time as indicated by the control group's performance improvement. This active practice during testing is part of the typical method for learning a new text entry system, and the results suggest that augmentation using passive training could provide significant benefits in this process. User performance typing the second pangram demonstrates the participants' knowledge of the full alphabet. Input performance results for each word show the effects of the intervention, indicating that a relatively short period of passive instruction leads to a large reduction in error. Similar performance on input tests and written tests suggests surprisingly good system usability. Users are keying Morse with relative ease – a potential secondary challenge posed by the input tests. With minor changes to eliminate the per-letter wait time, perhaps the same system could be used longitudinally to increase input speeds. Results show an interesting convergence of users' self-regulated, system-compliant dot and dash durations. Might different system thresholds change user entry speeds? Given the extensive amount of testing, we expect some learning over time in both conditions due to active exposure to Morse code during the tests.

Perception test results show that users who received PHL performed notably well. Users could receive silent, haptic messages after passive training. Might continued passive stimulation lead to rapid, accurate reception of silent communication too? This concept raises another issue. We taught users by having them receive Morse passively, yet when tested on both reception/perception and production skills, the participants outperformed on production! One explanation for this result may be that the perception test is ephemeral. Participants are only given one chance to hear the stimulus, while for the production tests the participants could control the timing. Even so, this success begs the question: Does exercise in reception rather than production result in better learning?

As an aside, this work also presents an example implementation of silent text input on a mobile device with no keyboard. Overall, users were successful at inputting Morse code on Glass by tapping with one finger. This result suggests that an eyes-free, silent input system can be achieved using a technique like Morse while requiring just a binary sensor. This feature is desired by users of wearable and mobile devices [74, 134], but is increasingly challenging because the streamlined nature of these devices precludes many standard text entry methods. In addition, there are learning costs and barriers that prevent the adoption of many non-QWERTY text entry systems [7, 54, 95]. Perhaps PHL can even be applied to help address the existing challenge for mobile devices and text entry learning.

6.6 Apparatus 2: Smartwatch

This section details the wearable computer and stimuli that were used to provide passive haptic training for this study.

Wearable device

Here I present a case of using a smartwatch for passive tactile learning. I use the Sony Smartwatch 3 to teach users Morse code while they wear the watch but focus on unrelated tasks. Smartwatches are commonly available wearable computing devices. The smartwatch's haptic element is typically a low-amplitude actuator designed for subtlety and to not drain power from the wearable [72]. If they can provide sufficient tactile stimulation, many more people could try techniques like passive haptic learning.

I selected an Android watch for easy, open-source programming. Four of the most common smartwatches including the Moto360, LG G, Sony SmartWatch 3, and Samsung Gear were considered for this study. The Sony SmartWatch 3 was selected for best affordability, battery life , and prevalence among smartwatch users. Haptics specifications are not publicly available for these watches, so I characterized the watch's stimulation. Data were gathered using an ADXL345 accelerometer and microphone. We used a setup identical to Laforce et al., who was measuring the vibration strength and amplitude of common cell phones [56]. The watch frequency and amplitude was found to be 0.517 g and about 210 Hz. Common haptic interfaces used in passive haptic learning typically have amplitude and frequency of 1.3 g and 200 Hz [121, 125]. Activation duration, but not typically amplitude or frequency, can be changed using code running on the smartwatch.

Teaching Structure

For this study, the smartwatch will provide haptic taps to teach 10 letters of Morse code. Letters are split into three words, and each word is taught separately on a loop. This word-based teaching design is chosen to allow incremental learning aided by semantic associations.

In addition, it is not known **how long** users must receive background stimulation in order to know the information being stimulated. Previous work in passive haptic learning used standard times, such as 15 or 20 minute learning periods[125]. Could less time be sufficient? I compare two conditions in this study to determine how much time of passive stimulation is necessary for this system. All users receive background instructional stimulation during the first 8-minute distraction task for each word. **Only half of users receive stimulation during the second 8-minute distraction task ("the 16-minute condition").**

Stimuli

A smartwatch and headphones are used to deliver the passive stimuli in this experiment. The watch stimulates a repeated sequence of Morse code on the wrist of the user. Dots and dashes are vibration taps of 250 ms and 750 ms respectively. Each group of dot and dash stimuli representing a letter is prefaced with an audio cue naming that letter. There is a 500 ms pause between each group of stimuli representing a letter. Each letter forms a rhythmic pattern tapped on the wrist.

6.7 Study 2: Design and Methods

I recruited six participants (19-23 years old, 5 male/1 female) to participate in a between-subjects study about learning from the tactile stimulation on a smartwatch [124]. I hypothesize that users may struggle to learn from the subtle stimulation produced by the smartwatch. The study begins with a brief verbal introduction to Morse code and a pre-test on all letters. The study consists of periods of passive learning, surrounded by brief tests to assess the user's progress. For each of three words, the study is as follows:

- Pre-test
- Stimulation and distraction task, 8 min.
- Middle test
- Distraction task, 8 min., with optional stimulation
- Post-test

Figure 6.14: Learning sessions setup. Participants focus on a game while receiving stimuli.

Measures

I measure user knowledge of Morse code before and after passive haptic training, using the percent of characters entered accurately. Users are tested on their production of Morse code using a smartphone app (Figure 6.15). They are asked to enter the '.' and '-' combination that represents each letter in the word they are learning. No feedback is given on the accuracy of their performance.

Distraction Task and Conditions

Stimulation will be passive, and the primary task from Chapter 3 [120] was used to occupy participants during the training. **Participants are told to not pay attention to the stimuli and to focus only on getting a high score at the game.**

During distraction tasks, users wear the watch and noise canceling headphones (Figure 6.14). **The vibration produced by the watch is the only thing that delivers any information about Morse code.** Only half of users receive stimulation during the second 8-minute distraction task ("the 16-minute condition"). The study ends with a post-test for all letters.

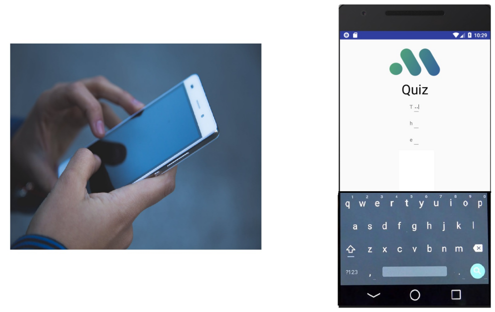


Figure 6.15: Testing screen. Users enter their answers on a smartphone app.

6.8 Results

Accuracy was calculated as the percent of totally correct responses in a test. All users showed significant improvement from pre- to post-test knowledge of Morse code (paired t-test $t(5)=11.62$, $p<0.001$). See Figure 6.18.

Accuracies for the pre-, middle, and post-tests for each word are shown in Figure 6.16. Users showed significant improvement between all pre- to post-tests, and pre- to middle tests on “dog” and “the.” Most users reached 100% accuracy on these words after just eight minutes of stimulation.

However, users showed lower scores on the middle test of “lazy.” All 16-minute condition users showed a 25-75% improvement after the second eight minutes of learning on that word.

Game scores were logged and found to be consistent with a prior study using this as a metric for distraction over 15 minute periods [125]. Several users agreed to come back for recall tests in the days following the study. They were asked not to review any Morse code in between tests. The recall test was identical to the pre/post-tests of all letters. These recall tests were administered 1 day (24 hours) and 3 days after the end of the study session. Results on the recall test were approximately consistent with the user’s result on the post-test (“study end” Figure 6.17); no significant difference was found.

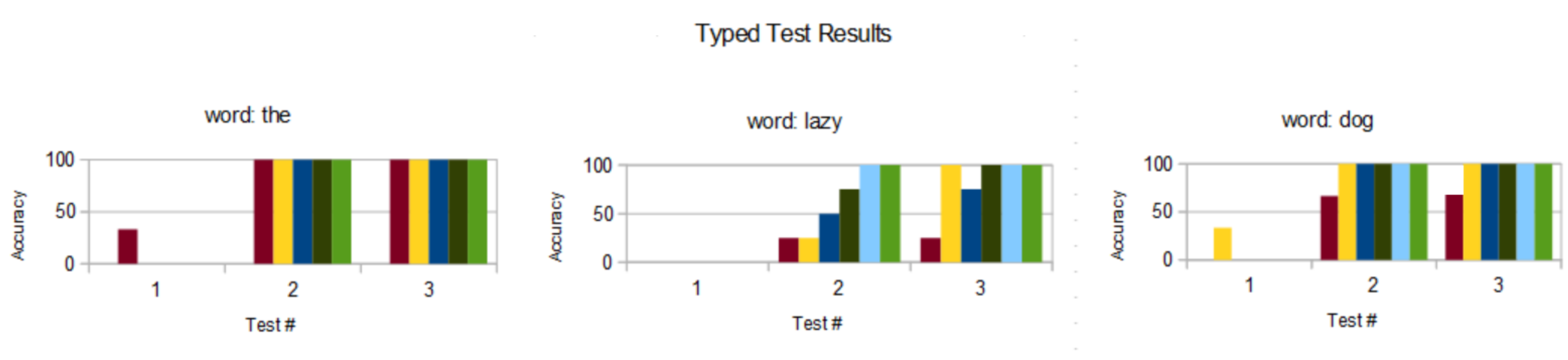


Figure 6.16: Typing test results for all word tests for all users. Each bar represents a user's test score. Yellow, dark blue and dark green bars are the 16-min condition.

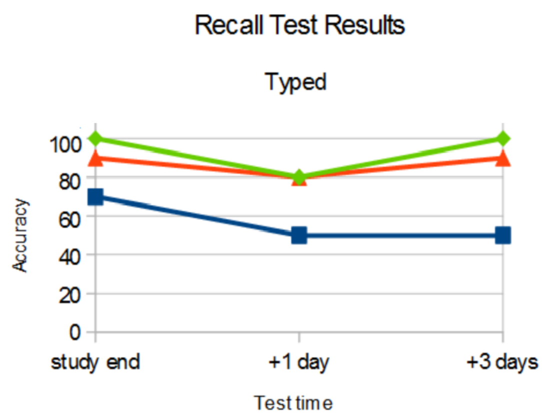


Figure 6.17: Recall test results. Each line represents a user.

6.9 Discussion

Results suggest that stimuli from the watch helped users learn Morse code. Though some errors are made when users reach the final post-test, near 100% accuracies on intermediate tests suggest that the instructional haptic stimuli were clearly perceived.

Learning seems to be in proportion to time exposed to stimuli. For the three-letter words, "the" and "dog" users reached near perfect after just eight minutes of stimulation. However, users were still showing improvements in the second interval of learning "lazy." Upon closer inspection, it can be seen that "lazy" contains nearly as many stimuli as the other two words combined (see Figure 6.19). This is the first finding exploring the effects of time/dose of passive stimulation on learning. Standard learning periods are used in prior research, but this work clearly shows that exposure time is an important and interesting consideration for this passive learning method.

Retention and recall trends are well known for other learning methods; however, a common but unanswered question is "Does the learning from passive training last?" The breadth of passive haptic learning research - from piano to rehab - has yet to explore this important question [73, 120, 122, 125]. Our preliminary probe of recall here suggests that learning may be more than short term.

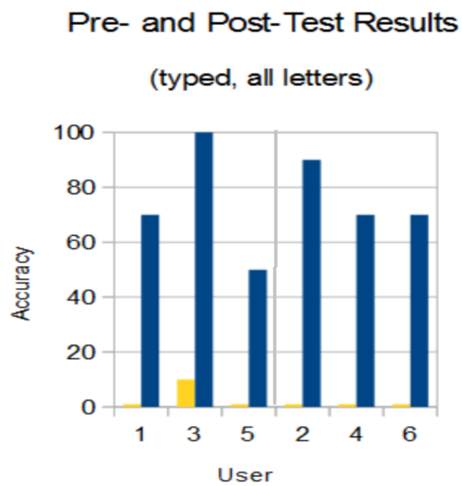


Figure 6.18: Pre- and post-test results for all users. Yellow bars are pre-test scores. Left-most three users are 16 minute condition.

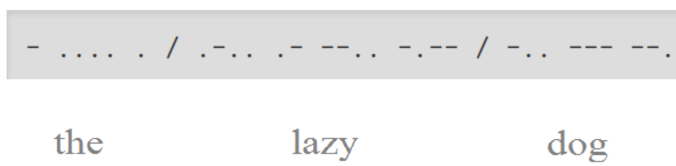


Figure 6.19: Morse code for each word. The word “lazy” has 14 characters, while “the” and “dog” have just 6 and 9 characters respectively.

Most of the vibrotactile stimuli were correctly understood as their represented dots and dashes. There were a few errors of the same type, where users entered the converse of the intended stimuli pattern (i.e., “–.” vs “..-”). Each letter is a pattern of short and long taps (dots and dashes) which form what feels like a rhythm. In this error case, from the researchers’ experience it seems that the rhythm gist was internalized (“–.” as “XXY”) but was mentally labeled incorrectly when translating the tactile rhythm into declarative labels (X=“.”). The stimulation design could be optimized to help eliminate this error, and it provides an interesting note on perception.

Other watch models, specifically the Apple Watch, contain more diverse haptic capabilities; likely using a customized LRA-type motor to produce a variety of stimulations. This watch platform may be able to encode even more rich information for learning [17, 120].

Commonly available wearable devices like smartwatches may be used to teach new skills using haptics. Future work will explore the potential applications of this technique and how such stimuli can be optimized. In addition, work should continue to investigate the question of how stimulation "dose" time effects amount of learning. Finally, does passive haptic learning enable lasting learning and how does retention compare to other non-tactile learning methods?

6.10 Conclusion

Two studies examined passive training of the Morse code system by translating the system into tactile rhythms. Results suggest that passive training successfully augmented learning of a rhythm-based system, and that stimuli can be successfully delivered on the head or wrist as opposed to the hands. The passive stimuli produced significantly increased knowledge of Morse with little additional active learning or practice. Users could input Morse code successfully on Google Glass using just a finger and could understand it silently through haptics. Passive stimuli did not inhibit performance on other tasks – a key component of the teaching method's potential for use during daily life.

The goal of this chapter was to train the Morse code alphabet and investigate the feasibility of using passive haptic training to teach rhythms. This system requires training discrete sequences of actions, but each sequence is defined by its time pattern. Prior work has not studied **training time-differentiated information** using passive training, but results suggest this is feasible. In this chapter, I also use **two commercial devices** to provide haptic stimulus (Google Glass and a smartwatch) – suggesting that others may more easily try this technique without custom hardware. In the following chapters, I study re-training motor skills in individuals who are disabled by stroke.

CHAPTER 7
BACKGROUND: STROKE AND REHABILITATION

In the following chapters I examine whether wearable, passive vibrotactile stimulation can help **re-train sensorimotor skills** in individuals who are disabled by stroke. This chapter serves as additional background on this neurologic event and current clinical and investigational rehabilitation strategies.

7.1 Stroke

A stroke occurs when part of the brain can not get enough oxygen. This deprivation is commonly caused by a blood clot or hemorrhage. After acute treatment, part of the brain often remains permanently damaged and this can affect the survivor's functions. This damage often occurs in the large sensorimotor cortex which controls sensation and movement, leaving stroke survivors physically disabled [140].

In fact, Stroke is one of the leading causes of disability in the United States and globally [71]. Disability is often asymmetric, primarily affecting one side of the body, and will be contralateral to the side of the brain where the stroke occurred (if in the cortex). Many stroke survivors lose function in their upper extremities, which can make it difficult to do everyday tasks like dressing or eating. Survivors are commonly effected in some or all of the following ways [41]:

- **Motor function**: Muscle control may be affected. Functional significance may range from weakness or loss of dexterity to complete loss of motor function/flaccidity.
- **Sensory function**: Somatosensory (touch, pain, temperature) and proprioceptive (position and movement) sensation may be disabled by stroke. Sensation levels may be reduced to insensate or only slightly diminished.

- **Tone and spasticity**: Survivors with affected limbs often suffer from spasticity. Loss of control from supraspinal (brain) centers can result in involuntary contraction and overactive reflexes in some muscles. The affected arm may be in a rigid position and fingers are often flexed into a fist, which impacts posture and limits range of motion. Spasticity and tone also present challenges to hygiene and dressing . Pain and long-term changes in tissue and tendons are also associated with spasticity.

- **Unilateral Spatial Neglect (USN)**: Attention may be affected by a stroke. Patients may not attend to or be aware of one side of their environment (contralateral to the stroke). This may result in symptoms such as: eating food only on one half of the plate and being unaware of remaining food despite intact vision, forgetting to read words on the neglected side, and failing to care for the arm on the neglected side.

Rehabilitation therapy is used to address these conditions and has the potential to lead to functional improvements. However, access to rehabilitation is a well-documented problem and current clinical techniques can be strenuous, ineffective or targeted only at those with mild disability.

Recovery of sensorimotor function could help stroke survivors become independent again, protect their limbs from injury, improve mental well being and allow them to return to a healthier lifestyle. Relief of spasticity and tone could improve hand function, promote recovery, ease dressing and reduce pain.

7.2 Access to Rehabilitation

Over 15 million people have a stroke each year. Five million survivors encounter chronic physical disability as a result, according to the World Health Organization. However, many barriers prevent recovery after stroke.

A new lifestyle of appointments becomes necessary, and many survivors require care and transportation from their support system. Many survivors must **travel** hours to reach physical and occupational therapy. When family members must return to work, rehabilitation often cannot be maintained. Patients, especially in developing nations, may have no access to post-acute medical care at all.

Costs for therapy are also significant: for Veterans alone, an estimated $186 million is spent in inpatient care and $88 million for rehabilitative care in the six months post-stroke. Many survivors are left **without insurance coverage** approximately six months after their injury [61, 136].

7.3 Current Methods and Practices

Although stroke is the leading cause of disability in the United States, current rehabilitation options are limited for survivors [104]. Repetitive mobility exercises are the most pervasive state-of-the-art therapy; other methods are more rarely used and may require room-sized devices or experiential medications. Constraint-Induced Movement Therapy (CIMT) and related methods are the only techniques with widely-proven efficacy [147]. In many cases, motor disability can be reduced with intensive therapy (often in-patient, 6-8 hours per day), but this intensity **can be strenuous and exhausting** for participants. Without intensive therapy though, repair will stagnate and result in minimal improvement. **Adherence is also a well-documented problem** with this technique. Recovery requires commitment, and is often abandoned by eligible practitioners due to the time and focus it requires. And in addition, **approximately 50% of survivors do not qualify** for this exercise-based therapy because of limited dexterity [147], and barriers to access further limit the number of individuals that can benefit from this method.

Most stroke survivors who are moderately to severely disabled opt for weekly or bi-weekly physical and occupational therapy appointments. During these visits, survivors do exercises with the therapist and are taught compensatory strategies or ways that their caretakers can help with tasks such as mobility. Survivors may also enroll in studies or try investigational techniques.

In addition to weakness, increased tone and spasticity are major causes of impaired arm function after stroke, with around 40% of survivors affected [34].There are currently very few effective treatments for tone and spasticity, and existing treatments have notable drawbacks. Intramuscular injection of botulinum toxin type A (Botox) is used to relieve tone, but may not impact underlying causes of spasticity [37]. The injection form factor is invasive, costly and can be painful for recipients. The treatment must be readministered every 3-6 months, requiring routine visits to the clinic [31]. Baclofen (along with related drugs) is also used to relieve spasticity and tone. These treatments are systemic, can be associated with adverse effects and the need to ramp up dosage [24]. Many patients still exhibit spasticity and tone while receiving treatment [37].

7.4 Research Involving Stimulation

As an aide to traditional rehabilitation therapy, methods of body stimulation are being investigated.

Electrical Stimulation

Electrical stimulation can be used to induce muscle contraction, and is applied to help individuals with paralysis accomplish motor tasks (Functional Electrical Stimulation (FES)). This usually occurs during physical therapy exercises such as stationary bicycling, during which electrodes are applied to the skin of the disabled limb and a control unit helps activate the muscles. When the exercise is over the electrodes are removed. This method helps exercise paralyzed muscles.

Electrical stimulation can also be applied as sensory stimulation (Afferent Electrical Stimulation, Trancutaneous Electrical Nerve Stimulation (TENS), or Percutaneous Electrical Nerve Stimulation (PENS)). This technique, also using electrodes or gel, is typically used for treating chronic nerve pain. However, some research has applied this afferent-level stimulation as a rehabilitation tool [51].

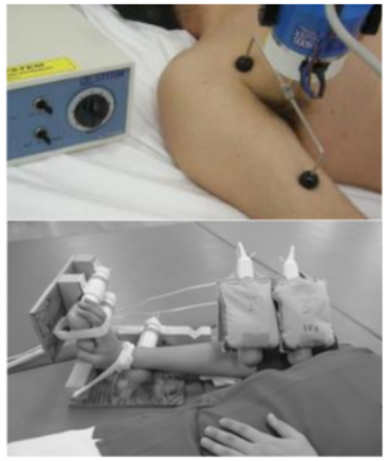


Figure 7.1: Examples of current apparatus for focal muscle vibration.

However, electrical stimulation presents a number of drawbacks as it may only be intended to exercise (not rehabilitate) paralyzed muscles, it can be invasive or painful, requires electrodes or gel, and is typically not mobile. Most apparatus for this method also take time and training to setup appropriately.

Whole-Body Vibration and Focal Muscle Vibration

There is encouraging preliminary data that suggests vibration may help improve motor function post-stroke. Whole body vibration (WBV) has been studied to relieve spasticity and enhance muscle strength [2, 36, 100]. Focal muscle vibration and tendon vibration have also been studied in normal and spastic limbs [15, 20, 26, 83, 91]. This work uses a clinical stimulation apparatus (see Figure 7.1) as the patient lays prone or sits in lab for focal stimulation. Results suggest that mechanical stimulation improves motor function and excitability. The systems used in these studies are or resemble the CROSystem (NEMOCO srl. Rome, Italy) [27, 44, 91, 105, 106].

Vibrotactile stimulation has also been combined with assistive devices and interactive games. One study applied wearable vibrotactile stimulation along with interactive musical therapy to five patients with partial Spinal Cord Injury and found significant improvements in sensation [92, 93]. On other work, robotic devices provide limb manipulation and vibrotactile stimulation to improve motor function [6, 29, 30]. Some of this work aims to enhance sensory-motor connections by ***repetitively*** applying enhanced sensory feedback during assisted movement [29]. Assistive devices such as robotics or exoskeletons are primarily investigational and often only available in a clinical setting. These devices can be costly, require the active participation of the user, and include physical manipulation of the limb or Virtual Reality (not vibration alone) [3, 30, 88].

7.5 Contribution

Wearable devices can now easily provide tactile stimulation for prolonged periods of time and in the background of other tasks. Vibrotactile stimulation activates a wide variety of sensory receptors which may provide powerful input to the neural circuitry. Unlike robotic limb manipulation or interactive games, stimulation can be passive – not requiring the user's attention or precluding other tasks. Yet the use of mechanical stimulation is primarily in conjunction with assistive devices or Virtual Reality.

Despite some encouraging preliminary data using vibrotactile stimulation for therapy [101, 91], **prior studies almost exclusively focus on the laboratory-based application of focal stimulus.** Rehabilitation requires intensive repetition, just as training and practice do, yet this can be strenuous or impossible for some stroke survivors. Just like in my work on haptic training, I suggest that by applying stimulation repeatedly for extended periods of time while the user focuses on other tasks, improvements may be found without requiring exercises.

My work aims to study the potential benefits of passive vibrotactile stimulation when applied for several hours per day using a wearable device. My results suggest that this technique may be a powerful tool for physical therapy.

CHAPTER 8
WEARABLE STROKE REHABILITATION

In previous chapters, I explored passive tactile stimulation for learning. In this chapter, I explore whether passive tactile stimulation, in the background of normal daily activities, can improve diminished limb function. Learning and rehabilitation are closely related; these fields share methods and goals [83, 146]. Learning and practice has the goal of creating or strengthening brain circuits, while rehabilitation after a brain injury can be a process of re-learning functions. Here I investigate its utility for rehabilitation, leveraging stimulation and repetition used in my work on learning motor skills.

Vibration provides strong activation of skin and muscle afferents which mediate and activate during normal movement [14, 69]. Some evidence suggests that vibration or tactile stimulation may be worth exploring as a neurorehabilitation technique [15, 83, 91]. This method bears further investigation, but no mobile device exists to administer and study this stimulation method at length or outside a clinical environment.

Wearable devices can now provide haptic stimulation for extended periods of time and in the background of other primary tasks – enabling passive haptic training. Can a wearable haptic device enable a novel therapeutic intervention as well? Individuals with physical disability from a brain lesion, such as post-acute stroke survivors, are in serious need for an accessible rehabilitating method to improve sensorimotor function. Here, I design a wearable device to provide haptic stimulation on-the-go or at home and perform two preliminary trials of this novel stimulation technique on stroke survivors with reduced upper extremity function. I hypothesize that vibrotactile stimulation administered for three hours per day using a wearable device can improve sensorimotor function in chronic stroke survivors, measured using standard clinical metrics.

Wearable Computing Challenges

This study requires a wearable computing device that correctly administers stimulation, is durable for at home use, and is accessible for users who may only have use of one hand. The devices will be taken home and used for approximately 56 days, with multiple interactions, don/doff and daily wear during that time. The device must be properly designed, with safety precautions and protections in place to reduce breaks and necessary repairs. For wearability, the device must be unobtrusive and comfortable in both fit and appearance. It must fit snugly against the skin to administer vibration, and power must be regulated to ensure standardized vibration strength. Accessibility is a major consideration, and preliminary design considerations were made to ensure participants could don and remove the device, plug it in, and turn it on with minimal assistance.

Rehabilitation Challenges

Research has begun to explore vibration for sensorimotor rehabilitation and spasticity relief. Preliminary results are encouraging, but prior studies on the upper extremities almost exclusively focus on the short-term, laboratory-based application of focal stimulus using a large machine. In this chapter, I present the results of studies using this stimulation for over 160 hours per patient – an intensity enabled by the use of a mobile, wearable computing device. The goal of this work is answer a number of key questions to inform design of this rehabilitation technology and enable further study into the mechanisms behind this technique.

8.1 Motivation

As detailed in Chapter 7, stroke survivors need more options for rehabilitation. Physical therapy can help patients recover some physical function post-stroke, likely because brain areas surrounding the lesion may adopt the responsibilities of the damaged area. However, recovery after a stroke is challenging, and clinical techniques for rehabilitation are limited. Survivors must re-learn the lost motor functions, just like they did when first practicing the skill. Survivors and their families face numerous barriers to accessing intensive treatment. **A mobile, low-effort therapy option may enable more people to recover function post-stroke.**

Research in animal models of stroke suggests that peripheral stimulation may induce some recovery and remapping [83]. Vibrotactile stimulation may be a promising treatment option, as there are promising preliminary results in whole body vibration and focal muscle vibration. However, neither of these are mobile systems that can be used outside the clinic during other activities. **A wearable device can provide intensive stimulation on-the-go – possibly reducing travel time, costs, and allowing study of a novel therapy method that may have significant impact.** The successful execution of this project could impact healthcare delivery, as this method may provide a mobile, affordable rehabilitation option for patients who otherwise would not have access to high intensity stroke rehabilitation due to geographic, financial, or dexterity limitations.

8.2 Apparatus

I designed wearable computing gloves to provide tactile stimulation to participants throughout their daily life activities (Figure 8.3).

Wearable Device

The device is a fingerless glove with vibration motors attached inside the fabric at the locations shown in Figure 8.4. Harbinger Flexfit Lifting gloves are adapted as the base fabric for this study. Small, coin-shaped vibration motors from Precision Microdrives (ERM-type, Model 310-113) provide stimulation (vibration strength 1.3 g and 175 Hz vibration frequency). Wires are sewn or glued onto the glove for reinforcement and connect to the circuit board.

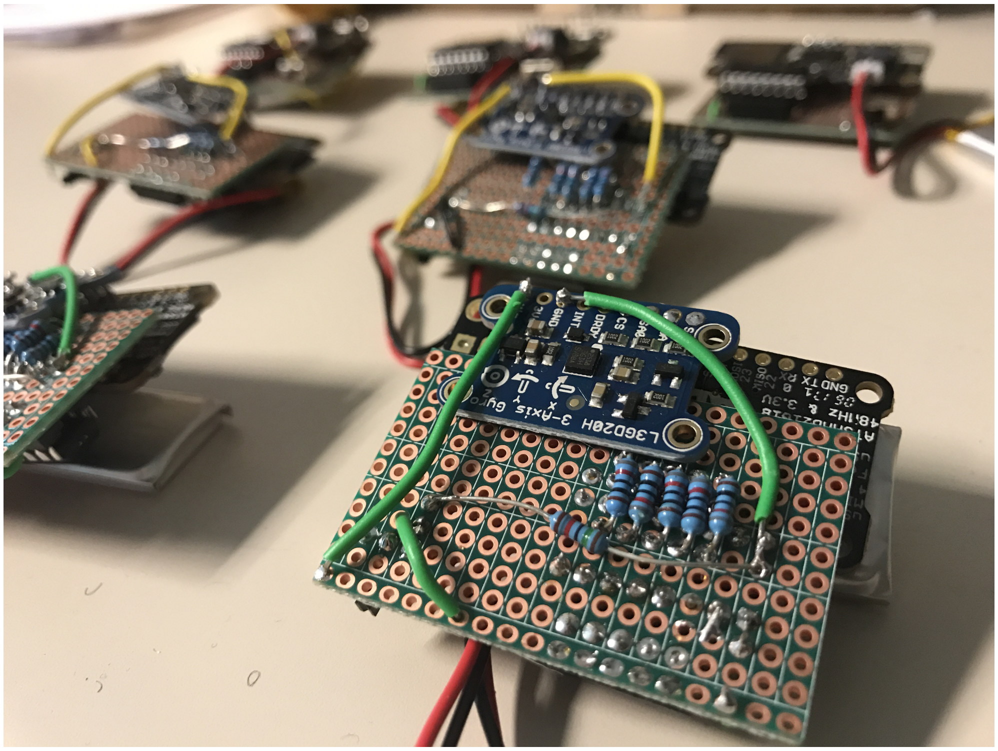


Figure 8.1: Close-up of the triple-decker board I designed for this study.

The heart of the device is a circuit board and microcontroller. This board contains the following: on/off switch, transistors and resistors for driving vibration motors, adapter plug for the gloves, a small low energy gyroscope board and a microcontroller board with native SD card. This board is pictured in Figure 8.1 and 8.2.

The board contains the *Adafruit Feather M0* microcontroller. The microcontroller orchestrates the stimuli patterns by reading instructions from a text file on the SD card. The Feather board was chosen because it contains a power regulator such that voltage to the motors remains constant at 3V (even when battery runs low, stimuli for the patient remains uniform). The triple axis gyroscope (L3GD20H) detects vibration and movement of the user, this helps log usage time. A lithium polymer battery and charging circuit allow users to plug the glove into the wall to charge, then take the glove on-the-go.

To make the device wearable, I designed the circuity to form three layers – keeping the footprint of the layout small (2.5 in x 2 in.). The board and a battery fit inside a 3D printed

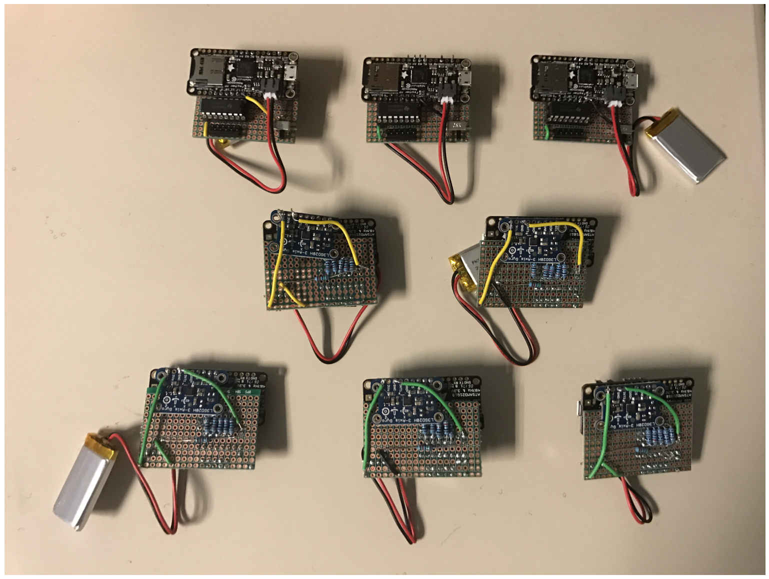


Figure 8.2: One group of boards I fabricated for this study. Front and back of the boards are pictured, with attached battery.

box with an easy pop top. This box was refined with user input and is designed to be accessible to those with limited mobility. This box attaches to the back of the glove using velcro and rests on the rigid metacarpal bones of the hand (so as not to impede bending of the knuckles or wrist). Average length for the smallest (pinky) metacarpal bone is 2.12 inches.

Stimulus Design

Vibration motors provide stimulation to the hand. Stimulation characteristics were designed to target cutaneous mechanoreceptors. Stimulation frequency was 175 Hz and amplitude was approximately 1.3 g. The glove stimulates each finger by activating the attached motor, individually in a pre-programmed sequence. The sequence is activated repeatedly while the board switch is "on" (for users not in the Control condition).

There were two sequences used, each based on a piano song. The song basis provided a framework to provide pseudo-random patterns and if users achieve fine dexterity they may be tested on passive training as well as arm function. The songs did not stimulate all fingers evenly, however. To address this, each song (Ode to Joy and Happy Birthday)

Figure 8.3: A group of left-handed gloves used in this study. Sized small (purple), medium and large.

Figure 8.4: Demo glove and motor locations on the proximal phalanx.

was extended with another sequence. This additional sequence balanced stimulation on all fingers, so that each finger was stimulated the same number of times each repetition. To provide stimuli of different activation durations, the sequence is stimulated twice each repetition: once with short activations (250 ms, 100 ms pause between each stimulus) and once with long activations (700 ms, 100 ms pauses).

The “song” was changed weekly, switching between the two sequences each week. These patterns are designed to provide on and off stimulus to each location, rather than continuous stimulation. Continuous stimulation at one location may lead to habituation.

8.3 Pilot Study: Design and Methods

This section presents an initial case study performed in Atlanta, Georgia to evaluate the effects of vibrotactile stimulation on upper limb dysfunction post-stroke. One stroke survivor was assigned to the intervention (vibrotactile stimulation (VTS) glove) for three hours per day for eight weeks. Limb function was measured during weekly visits throughout the study. This preliminary case study was not listed with clinicaltrials.gov but was approved and overseen by the Office of Research Integrity’s IRB board of Georgia Institute of Technology. The participant provided written consent before beginning the study. The Mini Mental State Exam (MMSE) is used to assess a participant’s ability to consent.

Participant

This study included one participant with stroke-related upper extremity deficits (age 64, 1.5 years post stroke). Table 8.1 details the criteria used in recruitment. I developed these criteria in consultation with previous literature and in collaboration with stroke researchers at Emory University Hospital. The participant was recruited through a local stroke support group.

I screened the participant against the recruitment criteria and accepted them into the study. During screening, it was found that the participant had left-side Unilateral Spatial

Inclusion Criteria
Ischemic or hemorrhagic (cortical or sub-cortical) stroke within 6 months to 5 years
Impaired touch sensation in the hand (Semmes-Weinstein monofilament exam score of \textit{diminished light touch (2 grams)} at 3 of 20 measured locations on the hand)
Passive range of motion hand can don a glove (help is okay if patient has caretaker)
English speaker age 18+
Exclusion Criteria
Insensate hand (Semmes-Weinstein exam, no sensation of 200 grams at 8 of 15 locations on the hand)
Intact sensation in the hand (Semmes-Weinstein monofilament exam)
Neglect (Star Cancellation Test score of <44/54)
Cognitive deficits, dementia or aphasia (MMSE score of <22)
Neurologic condition that may affect motor response (e.g., Parkinsons, ALS, MS)
Traumatic brain injury, subarachnoid, subdural, or epidural hemorrhage, AV malformation or stroke in the brainstem
No Botox in the limb or tone-softening medications (such as Baclofen)
Pain in the limb that substantially interferes with ADLs
Arm or hand injury/amputation limiting use prior to stroke
Enrollment in a conflicting study or undergoing any other upper limb rehabilitation during the study period

Table 8.1: Recruitment criteria for the pilot study.

Neglect ("left neglect"). I designed the criteria to exclude patients with neglect because stimulation on this side might not register in the brain in the same way as in patients without neglect – therefore stimulation on this side may not be effective. However, neglect is a problem with attention. I aim to provide **passive stimulation that does not require the active attention of the user**. This situation posed an interesting question as to whether the stimulation would impact recovery despite attentional problems. In the interest of exploring this question and commencing the study, this user was accepted despite the neglect.

At the first visit, the participant was given a glove device and a manual. The manual for the glove includes safety and use information. Participants are instructed to wear the glove for three hours each day and that the glove would track the time in use to measure study adherence. I assigned this three hours per day of stimulation because it may be a feasible amount of time that users could comply with, while increasing the duration slightly from related work which administers stimulation for 30 minutes - 2 hours, three to five times per

Semmes-Weinstein Filament Levels for the Hand
Normal Sensation (0.07 grams)
Diminished Light Touch Sensation (0.2 grams)
Diminished Protective Sensation (2 grams)
Loss of Protective Sensation (4 grams)
Residual Deep Pressure Sensation (300 grams)

Table 8.2: Filament sizes for the Semmes-Weinstein monofilament exam on the hand.

week [15, 92]. I also give participants an observation sheet each week for noting changes, problems with hardware, improvements, stories and anecdotes, as well as what the user was doing while wearing the glove. I met with the participant weekly to take measures of sensorimotor function throughout the study.

Primary Outcome Measures

I hypothesized that sensory stimulation (vibrotactile stimulation) is most likely to induce improvements in sensation, based on prior work [93]. Therefore, in this pilot study our primary endpoint is cutaneous sensation. The Semmes-Weinstein Monofilament Exam (SWME) is used here to assess cutaneous sensation at 20 points on the affected hand. Small filaments are used to probe the skin and test for sensation. Participants keep their eyes closed and produce a verbal response when they can feel the stimulus. Each filament produces a stimulus of a different force, in grams (Table 8.2. Sensitivity to smaller forces (smaller filaments) equates to better tactile sensation. Locations on the dorsal and ventral side of the hand are assessed (shown in Figure 8.5). These locations were selected to measure change in cutaneous sensation on the skin receiving direct vibratory stimulation, as well as other locations on the hand including those most relevant to tactile interaction (e.g., the fingertips). This test has good intra-rater reliability and requires little training. This assessment is done weekly.

Secondary Outcome Measures

I hypothesized that vibrotactile stimulation may also be associated with improvements in motor function. Voluntary motor function is measured by the Active Range of Motion (AROM). Here, I measured degrees of voluntary motion for joints in the hand, wrist, elbow and shoulder of the user's disabled arm. This assessment was chosen because it is a fine-grained measurement that will detect small changes and can be measured even for participants with limited dexterity who may not be able to perform the Box and Blocks Test, 9-hole Peg Test or the Wolf Motor Function Test. This measure is taken at the beginning of the study (visit 0), middle (visit 4) and end (visit 8). I performed this measure for our initial pilot study. This test requires training. A clinician (Sarah Callahan, MOT, OTR/L, Occupational Therapist, and SCI Clinical Research Scientist) at the Shepherd Spinal Center in Atlanta provided instruction on how to perform the AROM measurement. In the second study a trained clinician takes this measure.

Because the participant had spatial neglect, I added a weekly measure for this condition. The Star Cancellation Test is used as a measure of Unilateral Spatial Neglect. This worksheet has good reliability and requires no training. This assessment is made weekly. Few treatments exist for this condition, but some activities are recommended: talking to people on the neglected side, placing the night stand on the neglected side, etc. I hypothesize that stimulation on the affected side may impact spatial neglect.

8.4 Results

Sensation

Figure 8.6 shows areas (in green) that demonstrated trends in improved sensation. Final deltas in level of sensation are indicated by the color of the green shaded area.

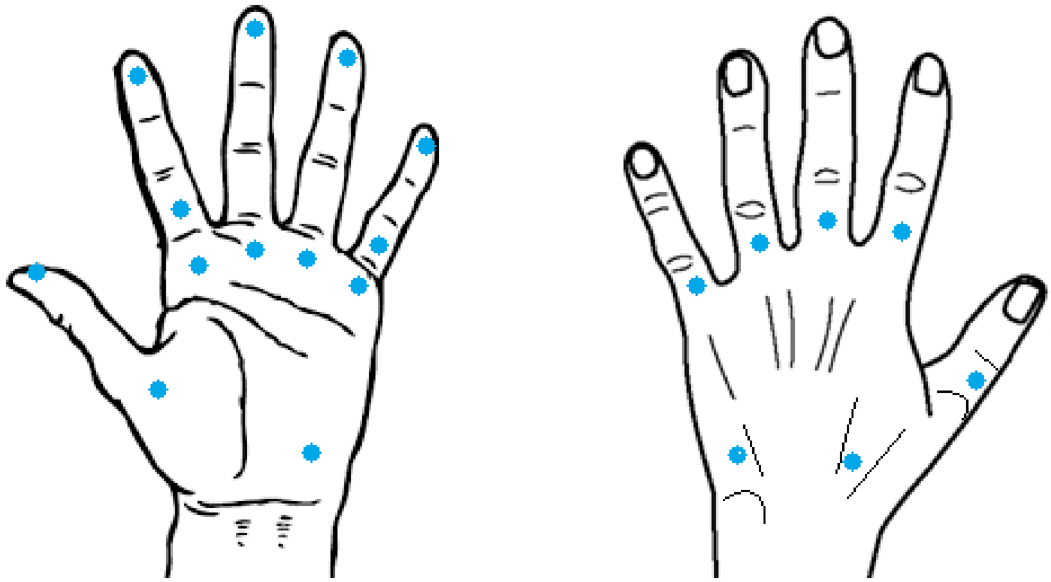


Figure 8.5: Locations where sensation was assessed on participants' disabled hand.

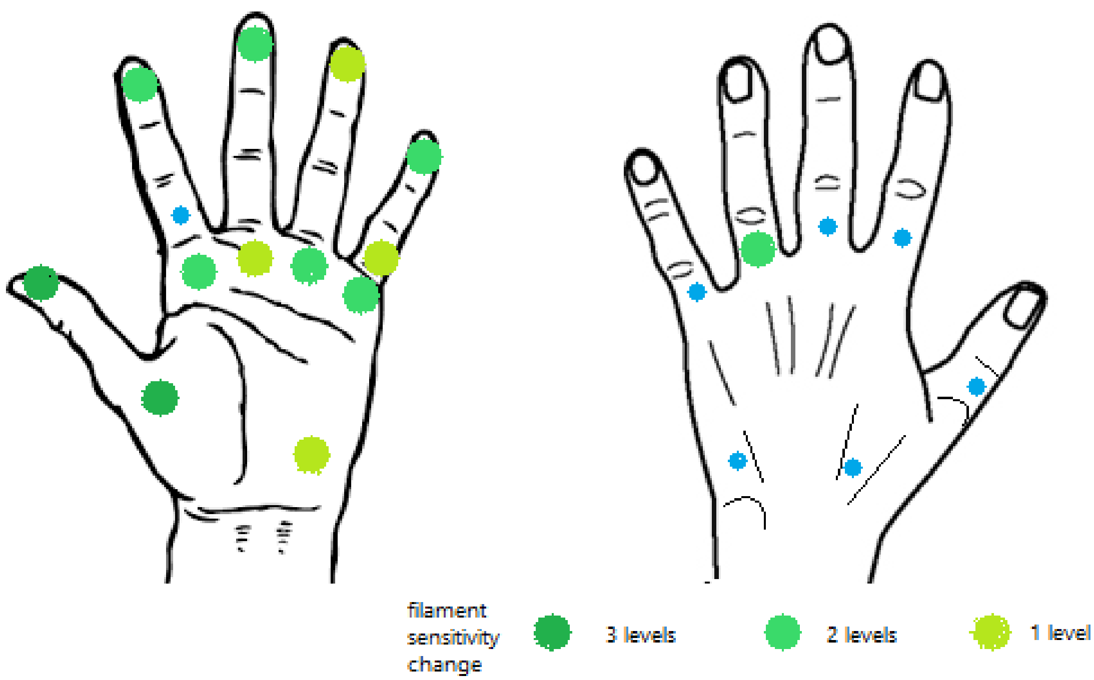


Figure 8.6: SWME sensation test results for the pilot participant, indicating the change from his initial level of sensation to the final measured level.

Movement

The participant's hand initially had very little voluntary motion. The participant could not demonstrate a pinch or extension and showed less than 15 degrees of voluntary flexion of finger MCP joints. The participant finished the study with more than 70 degrees of flexion in the MCP joints, with beginnings of abduction, extension and thumb IP movement. About 10 degree improvements were observed in the wrist and elbow (with observations suggesting potential for improvement in these locations as well).

I conducted the AROM measurements for this participant, and added trained clinicians to conduct all future AROM measurements to ensure accuracy. Video clips help capture movement changes for this first user.

Spatial Neglect

I measured spatial neglect each week using the Star Cancellation test. This test asks participants to draw a line through all of the small stars which are interspersed throughout the page. Users with neglect will be unaware that they miss some targets (stars) on the worksheet. For instance, a participant with left neglect will miss the targets on the left side of the paper. The Figure below shows results from the first and last week. A positive trend was observed throughout the study. The frontier of the participant's successful recognition progressed to the right, reducing the number of missed targets each week.

Spasticity and Tone

The participant started with some tone in the affected (left) hand. After three weeks of wearing the glove, the participant and spouse made verbal observations that the spasticity and tone had improved. Separately, the study administrator noticed a reduction in tone beginning around this time during evaluations of the hand. This improvement in spasticity and tone remained for the rest of the eight-week study. Video clips capture the change in tone to some extent.

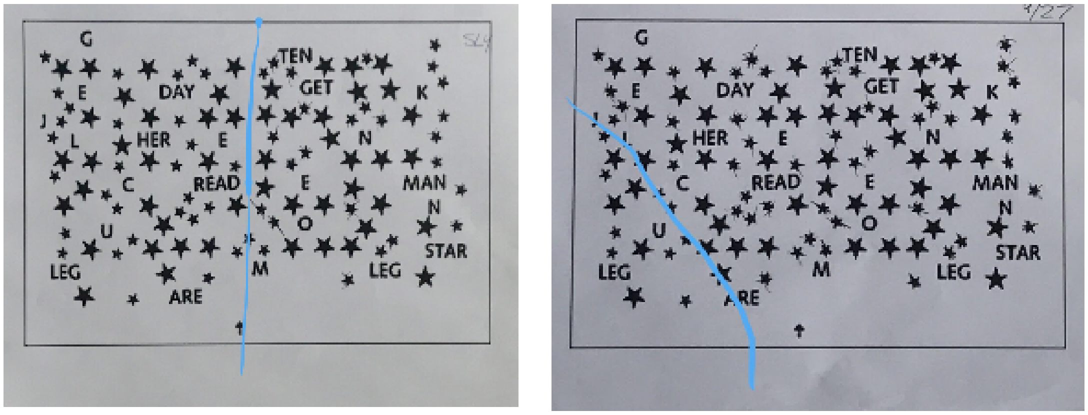


Figure 8.7: Stars recognized and crossed-out by the pilot participant - beginning of the study and end of the study. Blue line indicates the approximate horizon of attention.

I did not anticipate a change in spasticity and tone, so no discrete measurement was taken for this subject. For future participants the Modified Ashworth scale (performed by a physical therapist in initial, middle, and final study visits)) is used to assess tone quantitatively.

8.5 Discussion

The results and observations from this pilot study suggest that wearable vibrotactile stimulation may positively impact sensorimotor function post-stroke. Because of these results, further study was performed to assess the benefits of wearable tactile stimulation.

Spasticity and tone improvements were not anticipated, but were observed independently by multiple individuals, so the Modified Ashworth scale was adding to subsequent study rounds. For stroke survivors who exhibit spasticity and tone (about 40% of those with affected limbs), symptoms are often progressive – leading to more contracted limbs and increased disability and other problems. **There are few effective treatments for this sequelae. An effective, non-invasive treatment to address spasticity and tone could seriously improve quality of life and is worth further study.** Some research using WBV or focal laboratory vibration suggests that such stimulus may help mediate abnormal electrophysiology associated with spasticity, but further study is needed.

Increased sensitivity to cutaneous stimulation (our primary outcome measure) was observed. In addition, **changes in voluntary motion as well as spasticy suggest that this stimuli may impact range of motion.** Because of the notable change in these factors, we switch the primary outcome measure to AROM for the following study.

Performance on the Star Cancellation test improved throughout the study. **This result suggests that the participant's neglect may have improved throughout the eight weeks**. A post-hoc literature search reveals that techniques used to help recovery from neglect include increasing visual and verbal stimulation on the affected side. Many patients do not recover their abilities using the recommended lifestyle change treatment.. Can the stimulation from the glove help improve unilateral spatial neglect? I suggest future investigations be done on this concept.

8.6 Study 2: Design and Methods

The study was a single-blinded, randomized controlled trial performed in Atlanta, Georgia. Eligible participants were randomly assigned to a vibrotactile stimulation glove (VTS) or placebo control glove (Control) condition. As a feasibility study, the trial was not listed with clinicaltrials.gov but was approved and overseen by the Office of Research Integrity's IRB board of Georgia Institute of Technology. All participants provided written consent before beginning the study.

Participants

The study included 14 chronic stroke survivors with upper extremity deficits (ages 31-69; 1-12 years post stroke; 8 VTS condition/6 control condition). I recruited participants through stroke support groups in the Atlanta metro area. Table 8.3 shows a breakdown of demographics.

The inclusion criteria were:

- History of stroke >6 months prior
- Impaired touch sensation in the hand (Semmes-Weinstein monofilament exam score of >2 grams on 3 of 20 measured locations on the hand)
- Passive range of motion allows user to don a glove
- English speaker, age 18+

The exclusion criteria were:

- Intact sensation in the hand (determined by Semmes-Weinstein monofilament exam)
- Active Range of Motion within normal limits for all joints of the fingers
- Cognitive deficits, dementia or aphasia (MMSE score of <22) that prevent informed consent
- Other neurologic condition that may affect motor response (e.g. Parkinsons, ALS, MS)
- Pain in the limb that substantially interferes with ADLs or prior arm injury
- Enrollment in a conflicting study or any other upper extremity rehabilitation during the study period

User	Age	Sex	Years Post-Stroke	Side Affected	Baseline Notes	Outcome Notes
1	54	F	2 years	L	Insensate hand with almost no voluntary movement, wheelchair user	Recognized sensation at several test locations
2	31	M	3 years	L	Baclofen user, no Botox for one year	Reported ADLs: riding a bike and cleaning his guns
3	64	M	1.5 years	L	Wheelchair user	
4	54	M	13 years	R	Previously right hand dominant "Had not been able to use that arm for 12 years."	Reported ADLs: writing and helping to cook
5	67	M	1.5 years	R	Wheelchair user, seizures,	Full extension and flexion of fingers
6	48	F	3 years	R	Very limited mobility	"Now I call it my Iron Man arm" due to function/strength increase
7	49	F	9 years	L	Baclofen pump user, uncontrolled progressive spasticity, wrist fusion due to spasticity	Maintained relief of spasticity, can don winter gloves, can newly feel vibrations
8	66	M	1.5 years	L	Wheelchair user	
9	64	M	2.5 years	R	Golf exercise	
10	32	F	3 years	R	Good starting function, low dexterity	
11	53	M	2.5 years	R	Crossfit exercise	Some reduction in spasticity
12	68	M	1 year	L	Wheelchair user, starting Botox after the study	Reported better bladder control
13	66	M	1.5 years	L		
14	62	M	1.5 years	L		

Table 8.3: Demographics and notes for users in the study.

Individuals of various motor abilities were permitted to participate (from mild to severe deficit) as my wearable stimulation protocol includes no required exercises, making it suitable for individuals who have very limited movement. In fact, it is especially pertinent for patients with limited motion as few other options are available for those with at least moderate impairments. The concept behind this intervention is that passive stimulation may enable improvements while the user simply wears the device. This stimulation treatment may ultimately provide an accessible option for users with limited mobility. Therefore, in this feasibility study I examine whether recovery is possible using this method for various levels of sensorimotor disability post-stroke; further study can provide details on what markers, such as initial motor ability, predict outcomes using this device. As this investigation is preliminary, no prior data are available for power analysis.

Study Design

The study consisted of eight weeks using the stimulation or placebo device during daily life. Participants wore the glove daily and met with study administrators for weekly visits to measure sensorimotor function.

At the first visit, all participants received a device, cord and safety manual to take with them. Participants were instructed to **wear the device, turned on, for three hours every day** while awake. Users were notified that an onboard measurement unit would track usage time. All participants were advised to charge the glove each night using the cord provided, just as one might do with a cell phone. They could then wear the device on-the-go or at home during their normal routine. Hours wearing the device need not be continuous in a day, but should total three hours.

Intervention Condition

Participants in the vibrotactile stimulation (VTS) condition received a glove with vibration enabled. This glove stimulated their fingers using the method detailed in the Apparatus section (8.2). Unlike most interventions in rehabilitation, the intervention used here includes no required exercises. The protocol here aims to test a stimulation-only method of therapy, enabled by the wearable computing device and the novel vibratory stimulation method. Participants are told only that they need to wear their device for three hours per day, every day.

Control Condition

Participants in the placebo or sham condition (Control) receive a glove with vibration disabled. All indicator lights on the computer board activate in the same fashion as those in the VTS condition. Users in this condition are also told to charge and turn on their device in the same procedure used for the VTS condition. Safety instructions for placebo devices are the same. All users must frequently stretch their hand open to don the device, just as those in the VTS condition. Therefore, all factors except supra-threshold vibration were consistent across conditions. Adherence to wearing duration was required for both conditions and checked weekly via self-report and computer log. The control condition was assigned a sham device rather than no intervention in consideration of several factors: the goal of this study is to evaluate if the vibrotactile stimulation itself may have an impact on measures and results comparing devices may shed light on mechanisms underlying this technique (see 8.9 Discussion), related work and collaborators suggest using a sham device, and chronic stroke survivors (>1 year post stroke) are not expected to exhibit any spontaneous change in measures.

Outcome Measures

Baseline demographic information collected was sex, age, date of stroke, type of stroke, and side affected. The Mini Mental State Exam (MMSE) was used to assess an individual's ability to consent. Although there are minimal risks associated with the study, stroke can impact cognition so participants are given the MMSE at the start of the study to ensure they can give informed consent.

Measurements are taken during weekly visits throughout the study. These visits are also used to check on the patient and the device. During the first visit, initial baseline measurements are taken, the participant completes consent forms and is acquainted with the device. Some measures were taken by trained occupational and physical therapists not involved in this research. Those measures were taken at the beginning (Day 0), middle (4 weeks), and end (8 weeks) of the study. All other measures were weekly. These outcome measures were performed by trained individuals not involved in the intervention or data analysis. The therapist or study proctor for each participant was consistent to minimize inter-rater variability. Clinicians and proctors taking measurements were also blinded to condition.

Adherence **for users in both conditions** was measured each week using self-reported usage times matched with data from the glove's inertial measurement unit. If usage time was not within three hours of the required weekly time (21 hours) for two weeks in a row, the participant was released from the study. No such occurrences happened during the trial.

Primary Outcome Measures

The Active Range of Motion (AROM) is used to assess motor impairment. Here, it is measured for flexion and extension of all joints in the fingers, wrist, elbow and shoulder of the participant's affected upper limb. A trained physical therapist performed these measures in a clinical setting. This measure is taken at the beginning of the study (visit 0), middle (visit 4) and end (visit 8).

Secondary Outcome Measures

The Modified Ashworth scale (MAS) is used to assess tone and spasticity. In this study, MAS is measured for flexion and extension of all joints in the fingers, wrist, elbow and shoulder of the participant's affected upper limb. A trained physical therapist performs these measures in a clinical setting at the beginning (visit 0), middle (visit 4) and end (visit 8) of the study.

The Semmes-Weinstein Monofilament Exam (SWME) is used to assess sensory ability in the disabled hand. Locations on the dorsal and ventral side of the hand are assessed (shown in Figure 8.5). This test has good intra-rater reliability and requires little training. This assessment is done weekly.

The Star Cancellation Test is used as a measure of Unilateral Spatial Neglect. This worksheet has good intra- and inter-rater reliability and requires no training. This assessment is made weekly. For individuals who reported symptoms of neglect but did not score below average on the Star Cancellation Test, we added the Line Bisection Test. This worksheet prevents most compensatory strategies such as visual scanning.

A worksheet was also used to solicit feedback from participants. Participants were given a new sheet each week and told to write any notes for the day on both device usability and observations.

Statistical Analysis

Using an intention-to-treat analysis, we processed data for all participants including two who had to withdraw prematurely due to unrelated circumstances. I used the last measured values for the determination of any missing values in the case of dropouts or a missed visit, conservatively assuming that no changes occurred since last measure.

Change from baseline Semmes-Weinstein, Modified Ashworth scale and AROM were compared using the paired t-test for within a condition (VTS or Control); while differences between groups were compared using unpaired t-tests. A p-value <0.05 was considered statistically significant.

8.7 Results

Active Range of Motion

Motor function was measured in a clinical setting as the angular degrees of voluntary movement at joints in the fingers and arm. Each of four body areas are **summed (i.e., voluntary angular motion for shoulder is the sum of flexion, extension and abduction)**. Measures are taken in the neutral gravity plane whenever possible. Compensation from other muscles and synergy with spasticity are not included as voluntary range. Finger and elbow extension is measured from a flexed position, not from neutral, so as to report voluntary extension that may be used for activities such as releasing objects from grasp. **All fingers** are measured at MCP and PIP/IP joints and summed.

Starting means for arm motion and finger flexion had a significant difference between conditions. The control group included fewer members with low to moderate starting function. Baseline function may a factor to impact the control group, but further study is needed to examine its influence. The control group showed no significant difference in shoulder (M=186.8, SD=138.0, Avg.Change=11.33), elbow (M=99.67, SD=124.6, Avg.Change=-3.170), wrist (M=34.83, SD=38.80, Avg.Change=-3.667), finger flexion (M=500.3, SD=289.0, Avg.Change=50.5) or finger extension range (M=137.0, SD=120.8, Avg.Change=17.00).

The experimental VTS condition showed improvements in sum of shoulder (M=63.50, SD=71.58, Avg.Change=51.00), elbow (M=54.13, SD=56.15, Avg.Change=69.50), finger flexion (M=133.3, SD=140.2, Avg.Change=203.8) and finger extension ranges (M=45.57, SD=78.25, Avg.Change=228.8). A paired t-test found these changes to be significant (t(7)=2.59, 2.98, 2.16, 2.00, p=0.018, 0.010, 0.033, 0.043). Change in range of motion for the wrist (M=10.84, SD=13.84, Avg. Change=18.85) was not found to be significant. Changes are shown in Figure 8.8. Changes from baseline were compared between conditions and there was a significant difference between groups for the elbow, finger flexion and finger extension (unpaired t-test t(11)=2.64, 1.90, 2.04, p=0.01, 0.043, 0.034).

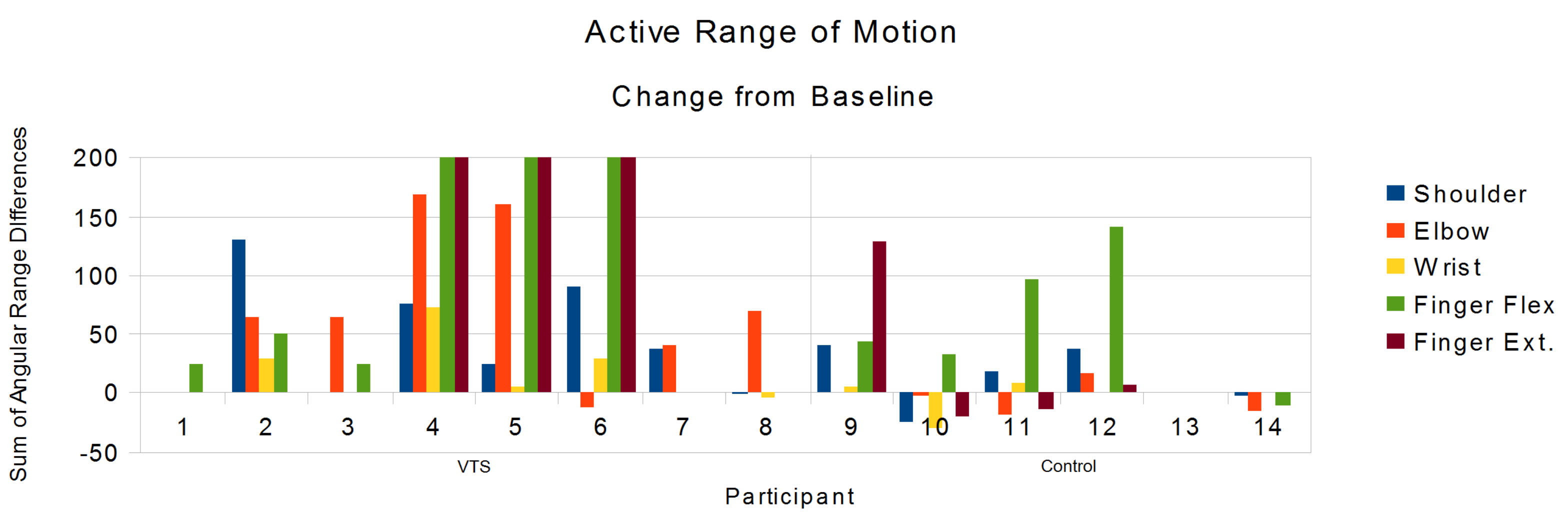


Figure 8.8: These data sum the increase in angular degree of movement for four upper body locations between the beginning and end of the study. Increases above 200 degrees (users 4-6, MCP and PIP changes for all five fingers) are truncated here to allow better representation of other data points.

Modified Ashworth Scale (MAS)

Modified Ashworth scale (MAS) was measured in a clinical setting for flexion and extension of all finger joints, wrist, elbow, and shoulder. Here, results are reported for the fingers (which showed the most change in values). MAS values here are reported on a scale of 0-5 and summed for the fingers. Starting means (M=26.75, SD=10.77 for VTS; M=25.83, SD=6.11 for control) were compared using a unpaired t-test ($t(12)=0.19$, $p=0.43$) and no significant difference was found. All users starting sums can be found in figure 8.7. Differences in experimental group MAS were found to be significant using a paired t-test comparing starting measures to measures at 4 weeks ($t(7)=-2.64$, $p=0.02$) and 8 weeks ($t(7)=-3.05$, $p=0.01$), with an effect size 1.08 (large). Average difference at 8 weeks was M=-13.75 total points on the Ashworth scale for the finger joints of the affected arm for users in the VTS condition. Differences in control group MAS at 8 weeks were also compared using a paired t-test ($t(5)=-0.70$, $p=0.51$) but the difference (M=2) was not considered significant. Change from baseline was compared between conditions and found to be significantly different (unpaired t-test $t(11)=1.91$; $p=0.040$). Differences are shown in Figure 8.10. User 5 had severe spasticity before the study, which led to a Baclofen pump and wrist fusion surgery. These interventions were failing to stop the progression of tone and spasticity in their hand; however, their tone was significantly less after participation in the study. Two users (5 and 7) agreed to follow-up six months post-study. There was no significant relapse in values at follow-up vs. study end.

Semmes-Weinstein Monofilament Exam (SWME)

Semmes-Weinstein Monofilament Exam (SWME) was measured weekly at 20 points on the hand and fingers. Figure 8.11 shows the average level of sensation for the hand over eight weeks for seven experimental group users and the average of the control group. One experimental group user is not shown because their starting measures prevent being represented on the graph. This user initially presented as insensate to all points, but could

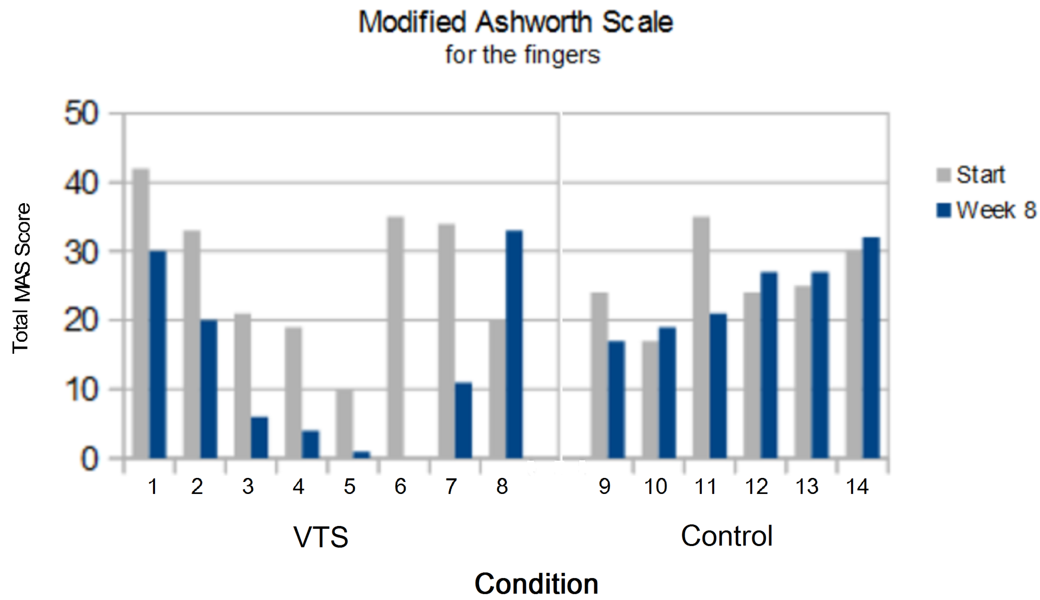


Figure 8.9: Sum of Modified Ashworth values for the fingers at baseline and after eight weeks. MAS values here are reported on a scale of 0-5. Lower scores are better.

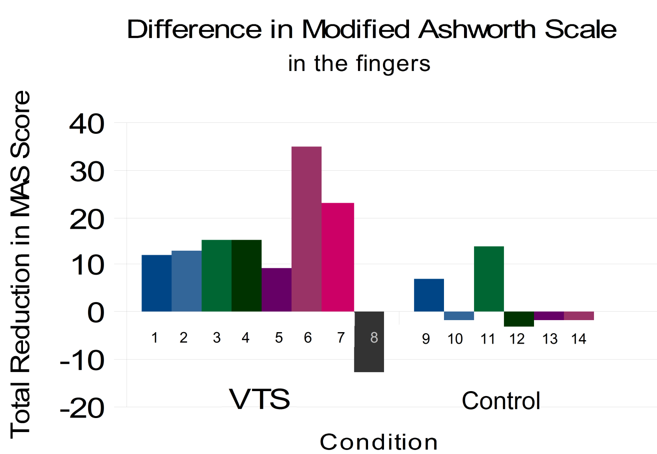


Figure 8.10: Difference in Modified Ashworth sum for the fingers from baseline to 8 weeks. MAS values here are reported on a scale of 0-5.

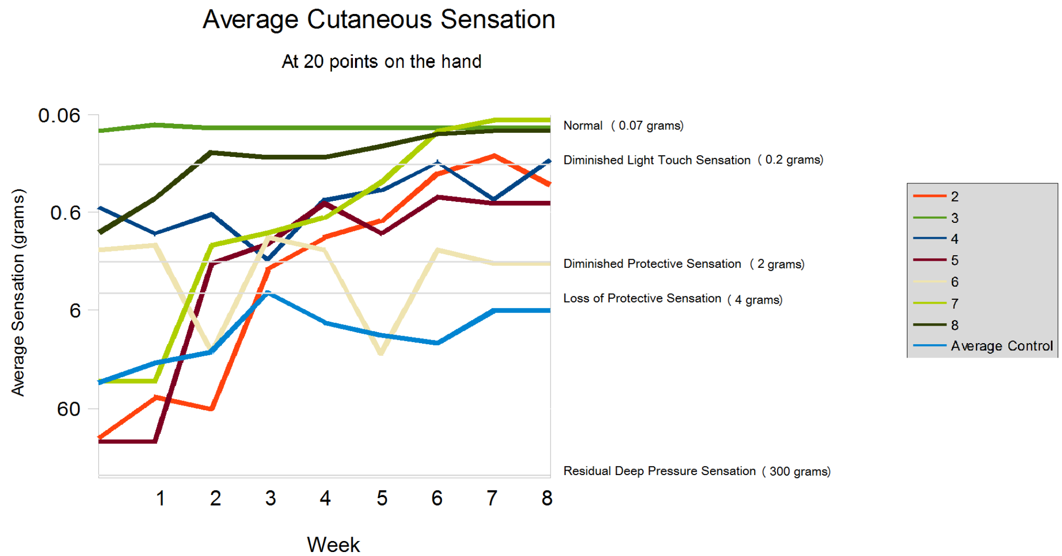


Figure 8.11: Trajectory of Semmes-Weinstein Monofilament Examination results over eight weeks. Each line represents a user in the experimental group, or the average of the control group. This graph shows trends in average level of sensation for the hand in grams. Smaller force values mean greater sensitivity. Logarithmic scale used to render all force levels.

accurately report deep pressure sensation at several points later in the study. Figure 8.12 shows averages for both conditions to compare trends.

Measures were taken at 20 points on the hand resulting in one force value per location, Smaller force values mean greater sensitivity. These readings were summed, with a minimum sum of 1.4 grams being "normal" sensation at all points and 6000 grams being only "deep pressure sensation" reported using the SWME. Starting means (M=832.4, SD=1205.5 for VTS; M=667.7, SD=1063.1 for control) were compared using a unpaired t-test (t(11)=0.259) and found to be not significantly different (p=0.400).

Figure 8.13 shows average starting (baseline) measures and average measures at the end of the study between conditions. Baseline measures of the VTS experimental group were compared to measures at 8 weeks (M=9.701, SD=14.25) using a one-tailed, paired t-test (t(6)=-3.50) and results suggest that there is a significant difference (p=0.006). As figure 8.13 shows, the VTS condition is able to sense smaller forces than the control condition at

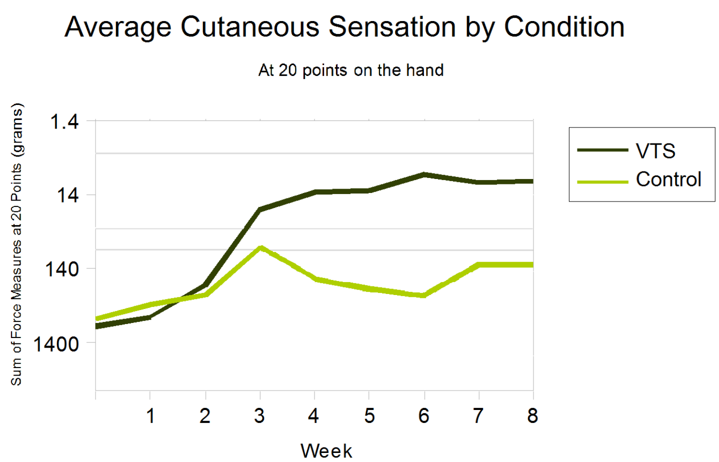


Figure 8.12: Trajectory of Semmes-Weinstein Monofilament Examination results over eight weeks for both conditions. This graph shows trends in sum level of force recognized on the hand in grams, therefore smaller force values mean greater sensitivity. Logarithmic scale used to render all force levels.

8 weeks (M=118.8, SD=256.1), meaning this group had better tactile sensation. However, the sham control condition also showed a significant change in cutaneous sensation (t(5)=-2.91; p=0.017). Changes from baseline were found to be significantly different between the groups (unpaired t-test (t(11)=2.32; p=0.020)).

Star Cancellation Test and Neglect

No users in this study had spatial neglect. Although some users reported symptoms of spatial neglect, none were registered on clinical tests.

8.8 Discussion

Results suggest that there were significant changes in Active Range of Motion, Semmes-Weinstein monofilament exam, and the Modified Ashworth scale after eight weeks of wearable stimulation. Changes in voluntary motion were found throughout the arm, but most in the fingers. These changes may be due in part to changes in spasticity that may have previously restricted range of motion. Users in the control group did not reflect the same

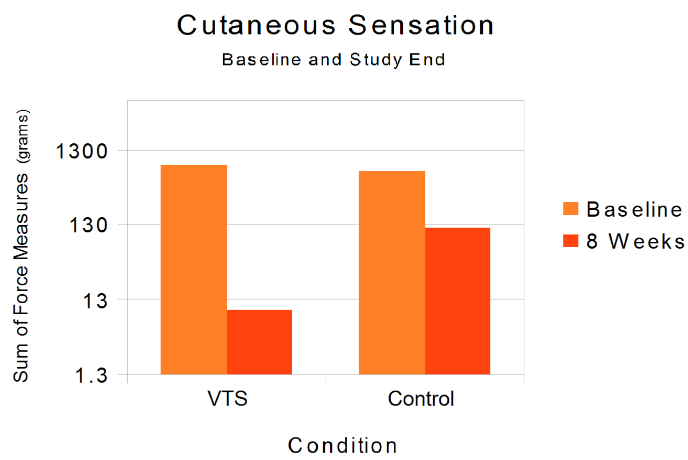


Figure 8.13: Cutaneous sensation on all points on the hand by condition: baseline and at 8 weeks. Smaller force values mean greater sensitivity. Logarithmic scale used.

changes, but also had fewer moderately impaired users who showed the most change in the VTS condition. Further discussion on results of this work is in 9.1.3.

Cutaneous sensation changes were found in both groups, but changes were greater for the experimental group. Figure 8.13 shows these differences. Users did not reach normal levels of sensation throughout the hand perhaps due to a ceiling in recovery, but Figure 8.12 suggests that the trend in improvement may not have reached a plateau by 8 weeks. This figure also shows a divergence in sensation trends between groups starting around four weeks that bears further study. One user in the VTS condition was not shown on these graphs due to their initial level of sensation (no sensation), however this user measured "deep pressure sensation" at select points later in the study. Others reported return of protective sensation in cases of joint hyper-extension and being able to feel the vibrations when they could not initially.

Participants, their families, and research assistants provided observations of spasticity reduction in the VTS condition. This is consistent with change from baseline Modified Ashworth scale measures. The VTS condition showed significant reductions in spasticity, while the control condition showed no significant change in the measure. Results suggest that the VTS intervention was associated with significant reduction of spasticity, and users reported an increase in ability to perform Activities of Daily Living (ADLs). Future research will include a metric to reflect this change in ADL function.

VTS participants in this study reported increase in protective sensation, sense of embodiment, and return to activities such as cleaning, cooking and writing using their disabled hand. One participant had a stroke more than 12 years ago and showed significant improvements in measures. That user was selected to participate to examine if the glove device might have an impact even on older strokes. Two participants were measured again at six months and showed no significant relapse in measures.

Laboratory studies suggest that focal or whole-body vibration may improve limb function, but none have explored a mobile form factor. Our non-invasive, non-focal vibrotactile stimulation at multiple locations on the hand is a novel method, and this preliminary trial is the first to examine this treatment at length. Some measurement visits were missed due to life events. This is to be expected in a take-home study involving stroke survivors. Events that impacted the study included: family issues, surgery, illness, weather, and seizures. This device was designed to provide **accessible therapy**: participants in this study were not currently eligible for other therapy options and would not have been eligible for methods such as CIMT due to their level of disability. Participants also took advantage of the **mobile nature of the device**: reporting wearing the device to events such as church, lunch, and the movies.

Effects of the Control Condition

Because the Control condition receives a device to wear on their affected limb, some changes in measures may be expected. **Any changes may help provide data on what mechanisms underlie changes using VTS and what changes may be attributed to the stimulation itself.**

The Control condition is a placebo or "sham." This condition provides attention and engagement with the limb which may discourage leaned non-use. Learned non-use [147] is thought to be one of the reasons behind limited functional improvement of limbs after stroke: survivors learn to compensate and do not force themselves to re-learn the use of their limb. Motor changes using this sham device were not significant, however more data are needed to confirm that users at all levels of functional disability would experience the same effects. Changes in motor function for the VTS condition but not control would imply that engagement with the limb is not the only mechanism at work in motor recovery.

Sensory changes were found for both conditions. The sham device provides cutaneous sensory stimulation via the fabric of the glove, while the VTS experimental device provides additional cutaneous, and possibly proprioceptive, stimulation via vibration. The significant changes in the Control condition suggest that the cutaneous stimulation from the glove, as well as other mechanisms of the study, may have improved tactile perception. The larger and less variable changes in the VTS condition, as well as the trend of Figure 8.12, suggest that the vibration stimulus may have impacted participants in additional ways or to a greater extent.

The sham device was known to include necessary stretching of the hand to don and doff the device multiple times daily. I expected this to impact spasticity and tone measures for both conditions, as stretching is one method to address progressive spasticity. Users in the Control condition did not show significant reductions in spasticity as the VTS condition did, however, suggesting that stretching is not the main mechanism for changed observed in the experimental condition.

Possible Mechanisms Behind Changes in Limb Function

Vibrotactile stimulation may induce sensorimotor improvements, as seen in preliminary data. A primary hypothesis is that such stimulation provides excitatory feedback and coactivation of motor systems (muscle and nervous), and helps to **restore somatosensation** useful in motor function [29, 38, 107, 109]. This is supported by work in sensory stimulation for motor learning and performance [117], and motor rehabilitation [30, 46, 51, 71]. Sensory stimulation may also **facilitate engagement with the limb** – helping discourage maladaptive plastic changes from sensory deprivation and learned non-use, a suggested key mechanism underlying constraint-induced movement therapy [53, 81, 147]. Investigation of these factors is beyond the scope of this work, but the promising results warrant further study.

Reduced threshold of the stretch reflex has been implicated as one of the mechanisms behind symptoms of spasticity [37, 108]. Supraspinal control usually regulates this reflex, but can be disrupted in events such as spinal cord injury or stroke [37]. These reflexes are also mediated by afferent feedback produced during limb movement [86, 128]. Vibration provides similar feedback – activating cutaneous mechanoreceptors and proprioceptive afferents [14, 43]. Vibration may help regulate electrophysiology associated with spasticity via this afferent feedback. **Afferent feedback then may induce** reflex suppression, involuntary muscle contraction and reciprocal inhibition (RI) - all of which can impact spasticity and are found during whole body vibration (WBV) and focal muscle/tendon vibration [2, 36, 91, 100, 101]. Presynaptic inhibition from afferent discharge is cited at the mechanism underlying reflex suppression during vibration [112]. Continuous passive motion is another treatment for spasticity, but removal of proprioceptive afferents was shown to prevent normalization [86, 103] suggesting that sensory feedback may underlie this change.

8.9 Conclusion

A controlled, randomized trial of 14 participants (8 experimental, 6 control) evaluated the feasibility of a wearable tactile stimulation method to reduce upper limb disability in chronic stroke. All users were assigned to wear a computerized glove on their affected arm for three hours per day. Users in the placebo Control group received no stimulation and those in the experimental condition received vibrotactile stimulation from the glove.

The wireless, wearable device was used during daily life, not in a clinical setting. Users who received vibrotactile stimulation demonstrated a significant change in measures of voluntary motion, cutaneous sensation and spasticity after eight weeks. Users in the Control group demonstrated a significant change in cutaneous sensation, to a lesser degree than the experimental group. Participants reported increase in protective sensation, sense of embodiment, and return to activities of daily living such as cleaning, cooking and writing using their disabled hand.

CHAPTER 9
DISCUSSION

Wearable computing enables haptic interaction for extended periods of time and in the background of other tasks. Results presented here suggest that this passive stimulation may aid training and rehabilitation applications.

Stimuli were designed to encode information or cue body parts for motor tasks with the goal of haptic training. The wearable form factor allows intensive repetition, and users' external focus during "passive" training did not preclude learning of normally challenging skills.

When stimuli were applied to limbs with diminished function due to brain injury, clinical metrics improved from baseline. Again, the wearable form factor enabled intensive repetition of stimuli without requiring movement or focus from the user.

Finesse is required in developing a system that enables passive training. This work has allowed me to identify several key features of system design. Here, I present guidelines to enable others to apply passive haptic training.

9.1 Guidelines

9.1.1 When to Apply Passive Haptic Training

Not all skills can be taught using passive haptic training; however, my results suggest that it may be a useful aide for a number of applications.

Motor Actions, Explicit Information and Recognizing Cues

Based on the results of this work, I suggest that motor skills and simple, explicit information are most amenable to passive haptic training.

When teaching **discrete motor skills**, training body parts directly using repetition of haptic cues may allow users to learn more rapidly. For motor skills such as typing, a tactile cue on the relevant body parts helped users recall these body parts when reproducing that action. Participants reported a sense of "muscle memory" or the **immediate association of those body parts when cued to perform the corresponding action.** Passive haptic training may also have some advantages in this case: Having the skill encoded directly as tactile information may reduce confusion typically associated with producing motor actions from written or verbal instructions. This modality is considered one of the advantages of active haptic training [90]. The external focus of participants' attention during *passive* haptic training (focused on the unrelated primary task), may reduce common cognitive bottlenecks that occur when practitioners focus on motor skill performance [148, 149]. Further study is required to better understand any advantages.

Passive training may also be suitable to teach **explicit information that can be encoded by haptics**, such as facts, associations or sequences. Participants were trained using tactile stimuli which encoded explicit information, and **were then able to extract the information from memory.** One example case is Morse code - a system of codes and their associated meanings. Participants can be trained not only on the tactile patterns but also can reproduce the content in written form. Passive training may also have some benefits in this case; It may allow less time devoted to studying explicit information from a visual table or key. Furthermore, memories may be encoded differently using haptic training – which may allow a more durable memory or enable multimedia learning [22].

Some research suggests that passive haptic training may also be helpful to teach users to recognize tactile cues and their meanings [85]. It is unknown if this recognition improvement is simply due to increasing knowledge or improvement in the perceptual skill. **Passive haptic training may also allow users to improve recognition of tactons, messages or cues** by training one cue at a time using repetition.

Convey the Skill via Haptics

To use passive haptic training, the skill must be translated into tactile stimuli. Currently, discrete tasks are more amenable to training (e.g. typing), rather than continuous tasks that may be hard to translate into haptic stimuli (such as pitching a baseball). The task should be conveyed by an unobtrusive haptic interface (i.e., wearable vibration cues, not an exoskeleton) to allow for "passive" training that does not preclude other tasks.

Stimuli can convey explicit information (i.e., Morse codes on the skull), or map the skill directly onto the body parts that perform it. The skill should be a closed set of content/actions that can be broken into short parts.

Content

Passive haptic training is aimed at teaching skills or information, as opposed to conveying cues during other tasks. This training can be applied to help novices **learn** the basics of a system, and might also be useful for **practice** to maintain or improve performance. The results of this work suggest that various content can be trained using this method including: temporal information and rhythm (e.g. Morse code), skills involving multiple body parts, simultaneous or grouped items (e.g. Braille), sequences (e.g. piano), and discrete items with associated meanings.

Limitations

Some applications are not suitable for passive haptic training. Skills that include many or limitless actions would require proportional time for training and should be **limited to bounded set of information to keep training feasible**. Motor skills or information that is continuous rather than discrete may be **difficult or not intuitive to represent using haptics**. Abstract or "soft" skills like how to perform a good presentation probably can not be trained using methods in this dissertation, but may be amenable to other methods like active haptic cuing. Open-ended skills like writing composition or programming may be impossible to train because there is **no fixed answer** to these skills.

9.1.2 How to Apply Passive Haptic Training

My work on this topic has enabled me to identify several areas key to designing a system for passive haptic training. Here I outline these features so that others can apply this training method.

Wearable Computing System

To enable passive learning, the apparatus must deliver haptic stimuli in the background of other tasks. This passive stimulation could be achieved by mounting haptics in the environment where a user is consistently in physical contact (such as the arm of a chair), but may be best achieved using a wearable device. The haptic stimuli should be unobtrusive, so as not to interrupt or prevent other primary tasks. Tactile actuators, such as vibrating motors, can provide such haptic feedback without limb manipulation or bulky hardware. Custom hardware can be created, and many off-the-shelf commercial devices can provide tactile feedback as well.

There are a number of fundamental considerations when designing wearable computing devices including power/heat, network, privacy, and comfort. When constructing a wearable system for haptic training, there are several additional things to keep in mind:

- **Fabric:** The fabric is a key area of consideration for the system because **rigid fabrics like leather will damp and disperse vibration**, making perception challenging. On the contrary, fabric with stretch (such as Nylon) allow actuators to fit snugly against the skin without damping vibrations. Antimicrobial fabric helps keep the system hygienic, especially if the device will be shared or used for extended periods of time. Plastic or other solid attachments (such as rings) can be used to affix actuators to the body, but these pieces should be lightweight, attached firmly to the actuator, and be isolated from the rest of the system to allow the entire plastic attachment to vibrate.

- **Fit:** The wearable device needs to fit snug against the body. This entails accommodations if the system will be on users of different sizes. An example is using fingerless gloves to allow a good fit on a variety of hand sizes.

- **Reinforce:** The wearable device will be used in the background of other tasks, and therefore durability is a key concern. Weak points include seams, motor wire leads, and battery leads. The system should be reinforced using glue, stitches, heat shrink and underwriter's knots.

- **Localize:** The system must allow users to localize stimuli. This requirement includes considerations on stimuli design and activation, but also includes considerations within the wearable system. The appropriate vibrating motors should be chosen, such as 10-13 mm coin-shaped actuators. Larger motors require more power and battery capacity, weigh more, and each one covers a larger area of the body. Placement of the actuators is also a key design feature. The zones that are stimulated by each motor must be considered, whether designers aim to activate large or small regions of the body. The conduction of vibration, and the sensory receptors activated, varies depending on location and magnitude of stimulus. Special consideration should be made between **bony areas and stimulation on muscle**.

Teaching Structure

To teach a skill using passive haptic training, **I suggest the teaching structure is of paramount importance.** In order to teach meaningful skills using passive training, the skill must be reduced to very short lessons. The body of information or actions **should be broken into parts, and taught one-part-at-a-time using repetition.**

By teaching incrementally, difficult skills can be conveyed a little at a time while the user is focused elsewhere. For example, I aimed to teach the entire alphabet in Braille – so I **broke the alphabet into parts using a pangram sentence**. The sentence contained all letters of the alphabet, and each word in the sentence became a short lesson. As another example, I aimed to teach a music phrase using passive training – so I **divided the phrase in half** and taught one part, then the other. Finally, when I aimed to teach a keypad layout – I **divided the layout into parts by location**, and taught one ***row*** at a time.

Each of these parts is then trained using repetition. Repetition supports learning and practice [64]. Repetition also allows the user to have many chances to perceive the stimuli even if the device is jarred or their primary task precludes perception. Finally, the duration of training must be appropriate for the amount of content.

Stimulus Design

The design of stimuli for passive training should begin with a test of active recognition. **If a user cannot discretely perceive and understand the haptic stimuli while focused on it, they will fail to learn passively from it.** For example, simultaneous stimuli. Passive stimuli should be extraordinarily simple and concise. Here are key considerations:

- Vibration characteristics of 1-1.5 g and 150-250 Hz are used here and found to be sufficient. Amplitudes of less that 1 g were used in Chapter 6, but further study is needed to determine a lower bound. Amplitudes of greater than 1.5 g will be conducted throughout body structures (muscle, tendon and bone) which may interfere with localization. Vibrations at higher amplitudes may be disruptive or unpleasant. The 1.3 g amplitude stimuli used in many of these experiments already present some low levels of these drawbacks. 150-250 Hz should activate the mechanoreceptors and muscle afferents most responsive to vibration.

- Stimuli should not be administered simultaneously, even when encoding simultaneous actions or grouped information. A small temporal offset or sequential presentation of stimuli can be used instead.

- A 70-100 ms pause may be necessary between stimuli on adjacent body parts. This may be a result of overlapping receptive fields or inhibition of neighboring fields, or another mechanism.

- Audio cues should not overlap with tactile cues. In preliminary experiments, the audio stimulus needed to be presented immediately before tactile stimuli. The volume of audio cues may also impact distraction and perception.

- Stimuli should be temporally tight – meaning that the stimuli for each lesson should be condensed to activations around 400 ms, with minimal pauses in between. Longer durations and long pauses cause stimuli to seem independent and not grouped, and reduce time for repetition.

- Time-differentiated information and rhythms can be conveyed. In fact, turning stimuli into rhythms (for example, by changing one or two stimuli activations from 400 to 750 ms) may aid perception. It has also been suggested that rhythm information may involve more central processes in the brain such as timekeeping [110], in addition to sensation.

- To train users past initial learning, continued repetition of the introductory stimuli may be sufficient. This method was used to train keypad typing in Chapter 5, where stimuli were designed to teach the layout over one session, then these same stimuli were repeated for two more sessions of practice.

9.1.3 When to Apply Passive Haptic Stimulation for Rehabilitation

Further study is needed to determine **features that are predictive of outcomes using vibrotactile stimulation therapy**; however, the current work provides some initial data on this topic. This method and device, if effective, may be especially relevant to those who have diminished motor function, are far from clinics, or have limited insurance coverage remaining.

Spasticity, Sensory Function, and Motor Function

Results suggest that this stimulation method may impact spasticity and sensorimotor function for chronic stroke survivors. This stimulation method may be studied in cases of spasticity and tone. Mechanisms behind spasticity relate closely to the muscle activity mediated by 1a muscle afferent fibers that respond preferentially to vibration [14]. This non-invasive stimulation method, if effective, presents a number of advantages over current treatments for spasticity detailed in Chapter 7. Sensory function may also be impacted by this technique. Sensory stimulation was associated with improvements in tactile perception. Motor function is closely tied to spasticity, because functional range of motion depends on both of these factors. Range of motion may be a third feature of interest in application of passive haptic stimulus; however, both motor and sensory function showed a ceiling effect based on participant baseline measures.

Participant Baseline Measures

Certain participant baseline measures showed greater change than others. Participants with any remaining voluntary motion in their hand (of 20-40 degrees for a given motion) showed greater change than those with none (<10 degrees). This trend was also true for the other joints of the arm. In contrast to passive haptic training, **users here did not need to be able to feel the stimulation with their affected limb**. In stroke survivors, sensory (afferent) nerve connections of the arm should be intact even if they are not recognized by the brain. Users who began with near insensate limbs (and reported not being able to feel the vibration at baseline) showed significant improvements in sensory measures. Regions on the hand with sensory levels of *diminished protective sensation* (2 grams) or worse showed the greatest improvements in sensation. Spasticity improvements were found in the fingers for those with severe spasticity (requiring wrist fusion) and those with mild or moderate spasticity.

Because this experiment did not require participants perform exercises with their affected limb, this method may be especially suitable for **survivors with limited motor function.** These survivors, like my participants, would be ineligible for constraint-induced movement therapy or task-oriented occupational therapy because they lack the dexterity to participate. A stimulation therapy method may provide the advantage of being used with limited initial movement in the limb, or may be partnered with exercises if the survivor is capable.

Limitations

The level of functional disability of survivors may be associated with the magnitude of potential recovery. This work has not yet studied whether this technique can enable recovery of fine dexterity. Participants with no initial voluntary motion in their hand or arm joint(s) showed only trace improvements in voluntary motion. A ceiling effect was observed for cutaneous sensation changes from baseline, no user reached normal sensation at all points on the hand.

9.1.4 How to Apply Passive Haptic Stimulation for Rehabilitation

Further studies can inform how to optimize stimulation for rehabilitation; however, here I present several key considerations based on current work.

Wearable Computing System

All wearable devices require usability considerations such as power, size, comfort, and social acceptability. For rehabilitation devices there are additional considerations. Accessibility is a key consideration for such systems. Users with physical limitations such as those affecting use of their arm (i.e., spasticity or hemiparisis) need accommodations to their devices. Previous research on wearable devices for users with Spinal Cord Injury found that fingerless gloves facilitate a snug fit on different size hands and that palmless gloves are cleaner and allow gripping while doing other tasks [93]. Here, I found that users

Figure 9.1: Accessible areas to mount a wearable computing device in the presence of spasticity and tone.

with spasticity need wearable devices that fit on their limbs which may be contracted or stiff. My participants often had fingers which were tight or curled at the beginning of the study – making donning the glove difficult. Such flexor spasticity, is common [37]. I propose that mounting the device on other body areas may help address this (e.g., Figure 9.1). The muscles that control the fingers are in the forearm, and some work on vibrotactile stimulation focuses stimulation on the muscle belly (rather than the tendon or elsewhere) [91]. A forearm cuff device would not require users to stretch open tight fingers: just one example of a form factor accommodation for these users. Alternatively, different attachment mechanisms to the fingers could be designed that do not require opening the hand.

Other features of the device also require consideration. Buttons and switches should be large and accessible with only one hand. Enclosures such as circuitry housing should have easy-to-open lids, and a barrel charging plug is easier to insert and remove than USB. The device must also be durable and safe, as it will be used for extended periods without supervision or maintenance. Users should be able to charge the device overnight, like other commercial electronic devices, and wear it without a cord throughout the day. Here, a 350 mAh battery at 3.7V was small enough for integration into the device while also providing three hours of stimulation.

Stimulus Design

Stimulation design here is a balance between **practicality and physiology**. Small actuators provide stimulation for this wearable device. The number of actuator models that are suitable for integration into wearable devices is limited. This hardware consideration limits vibration characteristics that are possible. Frequency should be chosen based on the sensory receptors to be stimulated. Mechanoreceptors and proprioceptive afferents respond differently to different frequencies – targeting spasticity may suggest stimulating most for muscle afferents (i.e., 70 Hz [29]), while cutaneous stimulation for sensory recovery may be best at higher frequencies.

Related work suggests that amplitude does not significantly impact response rate of the sensory fibers [43]. But I suggest that amplitude is a key consideration due to transmission of vibration conducted throughout the stimulated body part via bones, muscles and tendons. Attenuation may be different for spastic and non-spastic limbs. This transmission may impact recovery zones. Amplitude also impacts comfort. Users may find higher amplitudes disruptive. Safety and comfort should be considered in light of user preference and any detrimental effects of long-term vibration. Long term effects of vibration, such as those found from years of tool use in construction workers, should be mitigated by the on-and-off structure of the stimuli and limited use time due to recovery and practicality. Amplitude choice should balance comfort and transmission.

The activation pattern of the device should also consider physiology. An on-and-off activation of each stimulation location may prevent habituation, and further study can reveal how changing this pattern impacts recovery. Location of stimulus should be chosen for device accessibility and rehabilitation goals. The device form factor will influence where stimulation can be provided. In addition, the goals of the rehabilitation should be taken into account: stimulation for recovery of tactile sensation may need to be applied to the skin with diminished sensation, small stimulation zones may impact dexterity differently, etc.

9.2 Observations

Testing on Procedural Skills and Declarative Information

In this work, **users of haptic training were tested on motor actions, explicit information and recognizing tactile cues.** In Chapters 3, 4, 5 and 6, participants were tested on motor skills: Braille typing, piano, keypad typing, tapping Morse codes. In Chapters 3 and 6, users were also tested on extracting explicit information from their tactile training, using written tests of Braille letters and the dots and dashes that compose Morse code. Users were able to **produce procedural skills and declarative information** from passive haptic training. In addition, in Chapter 6 as well as another paper not presented here [85], users who received passive training were also tested on recognizing perceptual cues: tactile patterns of Morse code, and Vibrotactile Skin Reading [85]. This work suggests that training can aid users in recognizing tactile cues or tactons – but it is unknown if this recognition improvement is simply due to increasing knowledge or improvement in the **perceptual skill.**

Learning Challenging Skills

Participants learned normally challenging skills using passive haptic training. For example, Braille typing and reading are often taught as separate skills. Training can take months of sessions, with the alphabet typically taught over four months [120]. In fact, Braille is just one example of the learning challenges that throttle acquisition of new text entry systems. In some cases, an entry system is an established necessity of an industry, but the challenge posed by learning to use the system acts as a barrier to its users. For example, stenographers can maintain 300 WPM using their typing system for closed captioning, but learning this typing method takes years, and schools of stenography report averages of 85-95% dropout rates [77]. This challenge is further exemplified by the lack of typing systems in commonplace use besides QWERTY. Researchers even try to bargain with the learning barriers by creating QWERTY-like systems [7, 95] – while making some changes that provide usability benefits. Even the established QWERTY typing system requires users to practice for hours to achieve “touch typing” as opposed to “hunt and peck.”

Users also learned to perform piano pieces using both hands, which is commonly considered to be too challenging for students [12, 39]. Typically, when learning a piece of music that uses both hands, piano students learn to play one hand and then the other before playing both parts together; though music research literature views it as more advantageous to learn both hands together from the start [12, 39, 118].

Finally, Morse code is also a challenging entry system. For those getting formal training as a recruit in the Air Force, a course is devoted to teaching the skill. For hobbyist radio operators, the system is often too challenging to learn from studying a key, and many abandon the pursuit.

For these challenging tasks, students cannot just “watch and learn” via observation. Previous research suggests that haptic guidance is “especially suitable for less-skilled subjects and in especially difficult discrete tasks [90].” For these tasks perhaps the **direct presentation of tactile cues**, rather than instruction from a visual key or verbal feedback, aids acquisition of the skill. In addition, perhaps ***passive*** training reduces confusion that typically accompanies initial learning. Users gain initial familiarity while they do not focus on the task, and focus can degrade skill performance [149].

Repetition

Repetition is a key feature of learning, practice and rehabilitation [29, 64, 104]. The projects in this dissertation all leverage intensive repetition as enabled by the wearable device form factor and passive “background” training approach.

The work presented here demonstrates learning and re-learning, enabled by passive haptic training. Learning is teaching the brain to perform a new task. Rehabilitation after a stroke is teaching the brain to perform an old task. As mentioned by Williams et al. rehabilitation is re-learning [146]. Infants must learn to use their arms and learn to walk, and some elements of successful rehabilitation after a stroke can be re-learning these functions.

Sensory Receptors Involved

Results shed some light on what sensory receptors may be activated by the stimulation used in this work. Users needed a small delay between simultaneous stimuli and stimuli on adjacent body areas. This effect could be due to large sensory receptive fields, characteristic of the Pacinian corpuscles which are known to respond to high-frequency vibration. Findings an additional perception study [123] suggest that recognition of the stimulus is not better at the fingertip. Most receptor types other than Pacinian have a higher density at the finger, while Pacinian are more evenly distributed. This observation suggests the Pacinian corpuscles were involved in sensing the vibration presented in the studies in this work.

Results regarding spasticity suggest the muscle afferents may be activated by the stimulus. These sensory fibers mediate the stretch reflex implicated in some symptoms of spasticity [37], and vibration is known to conduct through bone and tendon – likely reaching the muscles. These muscle afferents are also activated during normal movement. If vibration activates similar sensory feedback as normal movement [29], these afferents may be related to the feeling of "muscle memory" reported by participants that comes during training using stimulation. Results on sensory changes in chronic stroke again suggest that the cutaneous mechanoreceptors may be activated by stimulation as well: cutaneous sensory improvements suggest stimulation was in part cutaneous.

CHAPTER 10

FUTURE WORK

As a result of this work, there are a number of future directions in the areas of haptics, wearable and ubiquitous computing, and rehabilitation that bear further **study**. The guidelines and findings in this work are also intended to enable others to ***apply*** these techniques in the future.

10.1 Future Directions in Haptics

Passive or Dual Task Training vs. Active Haptic Training

Haptic training can sometimes confuse users. Some research suggests that users experience less confusion learning motor skills when they have an external focus or dual task training [5, 148, 149]. Might passive haptic training (haptic training while the user is focused on another task) reduce confusion and error during haptic training? How does this differ for novices and skilled subjects?

Haptic Training Stimuli

More work can be done to deliver localized, intuitive stimuli for passive haptic training. Work may explore the lowest amplitude vibration that can enable passive learning, use of other stimulation methods such as brushing or stretching the skin, does rhythmic information help improve training, and how to convey different skills using a wearable haptic interface.

Research may also seek to expand work on training time (preliminary work in Chapter 6). For example, how many repetitions are necessary for different amounts of information? The attenuation and mechanical conduction of vibration throughout the body structures of the arm also needs to be characterized. This conduction may impact training and the results of rehabilitation.

10.2 Future Directions in Wearable, Ubiquitous, and Applied Computing

Applying Passive Haptic Training

Researchers in wearable and ubiquitous computing may want to apply this training technique to new applications. The Apparatus sections in Chapters 3-6 and the Guidelines in Chapter 9 can be used to design systems to apply this training method. Example applications may include learning the gestures for a new interface, training to recognize a set of tactons or tactile cues, practicing instruments or dance, and improving typing on the QWERTY keyboard.

Wearable Devices for Users with Physical Disability

Wearable devices for rehabilitation need special accommodations for their users. Individuals with history of stroke may have hemiparesis and spasticity. Other conditions needing rehabilitation may have other physical limitations. User-centered design studies and interaction with end-users is necessary to provide further guidance on how wearable devices can be designed for users with limited mobility.

10.3 Future Directions in Neuroscience, Learning and Cognition

This dissertation focuses on wearable computing, but fields outside of computing may have new research questions related to this work.

Learning and Memory

Researchers may improve systems for passive haptic training by optimizing repetition structures and integrating quizzes based on literature on teaching structures. Future work may also explore whether an external focus improves performance when carrying out a trained skill. Participants reported better recall of trained information when they did not focus on recalling the training, but instead thought of other things.

Vibration produces afferent input. Afferent input is also produced during movement. Can repeated vibrotactile stimulation provide similar sensory activation to that of repeated practiced movements, thus providing a similar sensory memory to repetitive practice? Participants reported a sense of "muscle memory" from training – what role does afferent feedback have in motor memory?

Other work may explore the role of short- and long-term memory in passive training. Does passive repetition encode the sensory stimulus in working memory or convert it to long term storage? Results on recall and the automatic nature of performing the skills may imply there is a long-term component to this memory. For declarative information encoded using tactile training (such as Morse code components or Braille dots), how durable is learning versus traditional rehearsal of information from a visual key?

Rehabilitation

In my future work, I will be working to uncover some of the mechanisms which underlie changes in arm function after stimulation. Knowledge of mechanisms will enable us to optimize stimuli and may help identify predictive factors for best outcomes using this stimulation treatment. Other future work may apply this stimulation method to other neurological disorders that impair sensorimotor function, or apply this technique to the lower extremities.

CHAPTER 11
CONCLUSION

In this dissertation, I aimed to uncover new potential in wearable vibrotactile stimulation. Haptic feedback from wearable devices is primarily used for alerts and virtual reality; however, wearable computing provides unique advantages in haptic interaction. Wearable devices can now provide tactile stimulation for extended periods of time and in the background of other tasks.

Since repetition is key to practice, learning, and rehabilitation, stimulation for extended periods of time may enable **intensive** haptic training or mobile stimulation therapy. Training and rehabilitation require time, dedication and sometimes exertion. Stimulation in the background of other tasks can allow **passive** training and therapy without requiring movement or attentional focus from the user.

My work takes advantage of these unique considerations to develop wearable computing solutions to help address real-world applications, while informing what is possible using passive tactile stimulation and enabling others to apply these methods in the future.

Applications including Braille, Morse code, typing, Piano, and Stroke recovery were used to study passive haptic training and therapy. By breaking skills into parts and teaching one part at a time using repetition, **I outline how passive tactile training can help teach motor actions and improve skill performance, teach users to associate sensations with meaning, and teach information that can be conveyed via haptics.** Results suggest that passive haptic training can have a significant impact on learning a variety of challenging skills. The design specifications in this work serve to **help others apply passive haptic training in the future.** By using a wearable device to apply vibrotactile stimulation during daily life to hands with diminished function, I demonstrate that a wireless mobile device may provide therapy on-the-go or outside the clinical environment. My results on wearable stimulation for *re-training* sensorimotor functions **suggest that passive vibrotactile stimulation may be associated with increases in voluntary range of motion, improved cutaneous sensation, and relief of spasticity.**

Appendices

APPENDIX A
PERCEPTION STUDY: SIMULTANEOUS TACTILE STIMULI

In my preliminary work on training Braille typing, which requires simultaneous actions, I found that users struggled to recognize multiple simultaneous tactile stimuli. This study expands on existing research to explore simultaneous tactile perception on the hands. In other work, the counting of simultaneous stimuli across the whole body was studied for subitizing (rapid, accurate numerosity judgments, normally by the visual system, of up to about four items). No subitizing effect was found, and error occurred in counting judgments of the number of tactile stimuli across the entire body [49]. In my preliminary work on training Braille typing, which requires simultaneous actions, I found that users struggled to recognize multiple simultaneous tactile stimuli. This study expands on existing research to explore simultaneous tactile perception on the hands.

Can multiple vibration stimuli be perceived at the same time? We wish to create a wearable interface that presents simultaneous signals in a recognizable format. Thus, I conducted a study to examine whether participants can perceive and recognize multiple simultaneous tactile stimuli on the hands ("chords"). Because our participants had struggled to use interfaces with simultanious haptic signals, we hypothesized that people may not be able to recognize multiple simultaneous stimuli. Sixteen users participated in this study to provide data on the subject.

Apparatus

I created two pairs of gloves to administer tactile stimuli. One pair uses Precison Microdrives eccentric rotating mass (ERM) vibration motors (part #310-113) while the other uses Precision Microdrives part #C10-100 linear resonant actuator (LRA) motors. Both element types are the "coin" form factor and were selected for their small size and "wearability." We

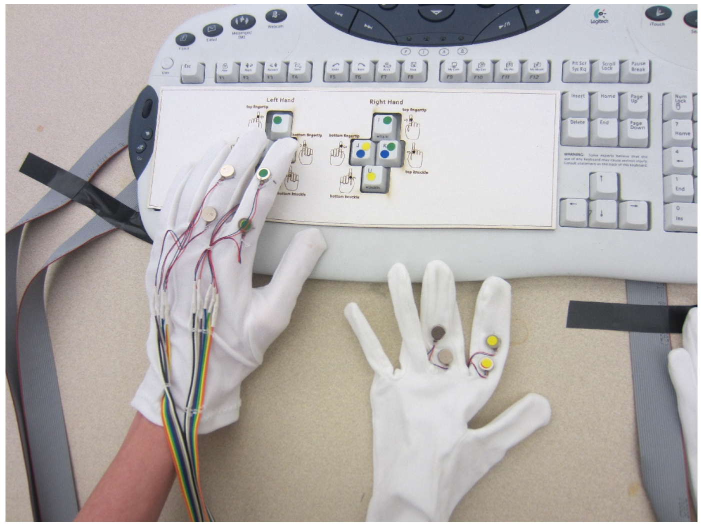


Figure A.1: A glove pair and the input interface for this study.

test the index and middle fingers in these studies to look for initial trends. Each of these fingers is outfitted with four motors, two on the dorsal (top) side and two on the ventral (bottom) side (positions A, B, X, and Y in Figure A.3). So each pair of gloves contains 16 vibration motors, eight per hand, with the flat coin side held flush against the skin. Note that I chose not to use position Z for this study as the vibration motors interfere with gripping in this position; we require our gloves to be practical during everyday activities.

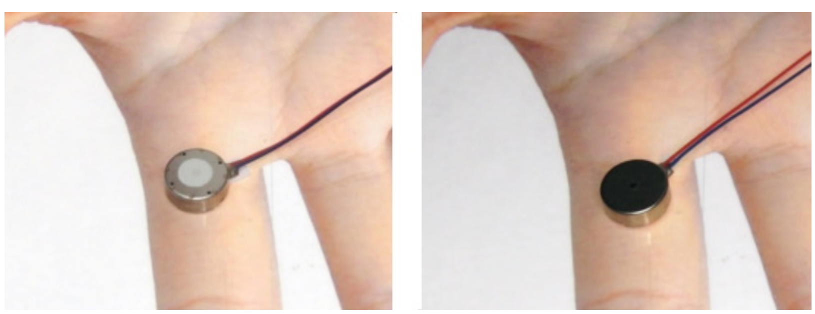


Figure A.2: The ERM and LRA motors. These lightweight, “coin” form motors are optimal haptic elements for wearable devices. From Precision Microdrives.

ERM #310-113 vibration motors Eccentric rotating mass (ERM) vibration motors contain an asymmetric mass and are powered by DC current [1]. We use 3.3 V DC to provide the constant current required for peak recommended vibration strength (1.38 g) and a 200

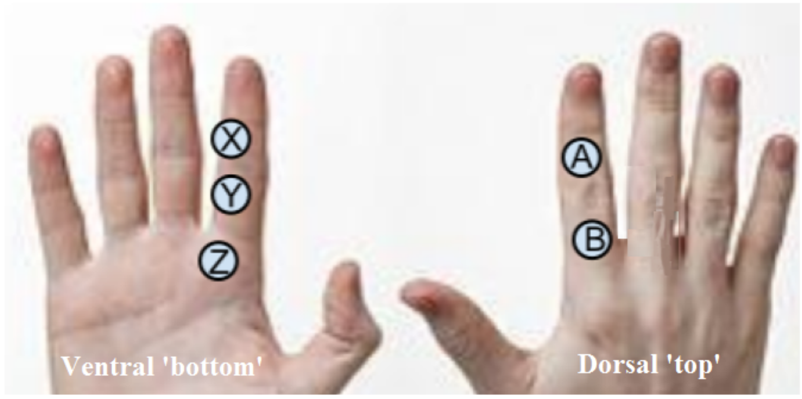


Figure A.3: Motor positions used in this and other of my perception studies. Alphabetic labeling is for reference in this paper for simplicity and is never presented to participants.

Hz vibration frequency (vibration frequency increases proportionally with applied voltage). These motors are driven by TI ULN2003 Darlington array chips to buffer the system's microcontroller and provide the necessary amplified current.

LRA #C10-100 vibration motors Linear resonant actuator (LRA) vibration motors became available on the market relatively recently and are designed for a longer lifespan and a more precisely targeted vibration than the ERM motors. The mass inside an LRA motor vibrates along an axis (rather than eccentrically) and is most efficient (highest output amplitude) at its resonant frequency. The resonant frequency of our LRAs is 175 5Hz [82] and is detected and maintained by 5 V DC Texas Instruments DRV2603 surface mount driver chips which provide AC current at the required resonant frequency. For these studies, we drive the #C10-100s at their peak amplitude of 1.4 g.

User Response Interface

In these studies we administer stimuli and ask the users what they felt. A standard desktop keyboard was adapted to collect responses. An overlay exposed only the keys used for the studies and provided a diagram that reminded participants of the mapping between stimuli and responses (Figure A.4).

Input mappings were chosen for their intuitiveness after testing on team members. Par-

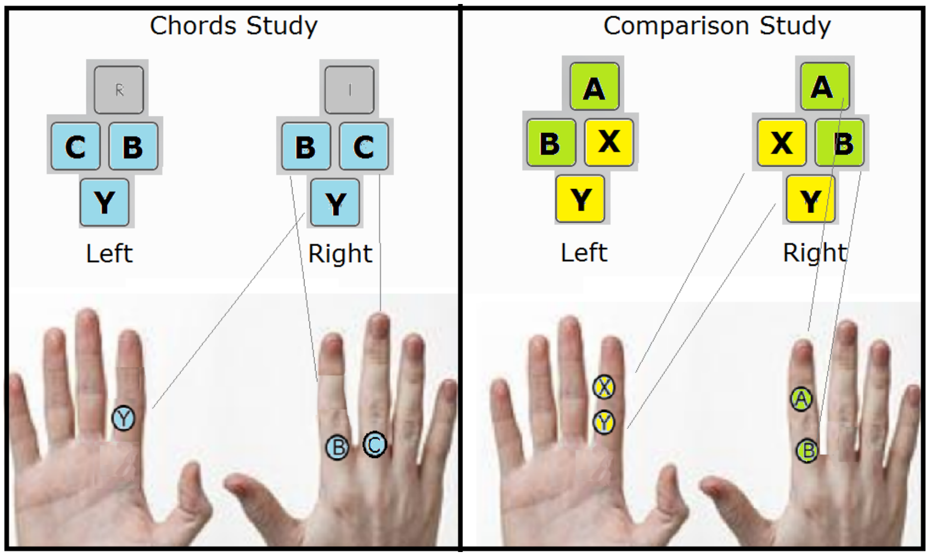


Figure A.4: Key mappings used this study (left) and other studies (right): each key's corresponding motor position is shown here on the right hand. Participants are told to use these mappings to input responses to stimuli. Users are presented reference diagrams and color codings, not the alphabetic codes in this image.

ticipants press the keys of the motors they identify as having vibrated in the last stimulus and may enter keys sequentially or simultaneously. For this study, three keys for each hand are used, corresponding to motor positions B, C, and Y as shown in Figure A.4 left. There is a one-to-one correspondence between vibrator motors and keys. Resting the fingers above the input keys places the motors near their corresponding key. Participants use the stimulated finger to indicate their responses.

Study Structure

Users are told to expect one or more simultaneous stimuli and to try and correctly identify all points of vibration and enter their answer on the keypad. Participants then don their assigned first pair of gloves (ERM or LRA), and the software begins delivering stimuli and logging response data. When all stimuli have been presented and users are done with their final input response, administrators help the user switch gloves, and the study repeats for the new pair. Glove orders are randomized and counterbalanced. Participants wear headphones to mask audio localization cues.

We chose to use the dominant two fingers of each hand to compare adjacent-finger and two-hand simultaneous stimuli of up to four points in our chords study. If this study showed high perception accuracy, we would expand the study to include chords on all fingers. However, we first want to establish that chorded perception is possible. All permutations of one-, two-, three-, and four-motor combinations of motors in positions B, C, and Y on both hands were examined. This technique allows examination of chords on adjacent fingers on the same hand, chords across both hands, and chords containing stimuli on the top and bottom of the hands. It also tests the motors individually to examine whether users can identify multiple chorded stimuli versus single stimuli.

Activation duration was consistent throughout the chords study. Simultaneous motor groups (or individual motors) were activated together for 300 ms during each stimulus. This duration was used in previous work [49, 126] and allows time for our ERM motors to reach full-speed. Each stimulus was delivered twice for each possible set of chords (four times total – twice for each glove type).

Results

Numerosity Judgments The number of vibration points that users sensed and recorded (numerosity judgment) was calculated using the number of inputs they entered for each presented stimuli set. This data was averaged and grouped by the actual number of stimuli delivered in that set. As illustrated in Figure A.5, users average 1.09 and 1.94 points sensed respectively for single stimuli and chords of two stimuli. T-tests suggest that for numerosity judgments of one and two stimuli there is not a statistically significant deviation from ground truth, for either motor type (ERM and LRA) or on the average. Users under-sense stimuli sets of three or four, with average points sensed of just 2.51 and 2.77. T-tests show a significant difference in user judgments compared to ground truth (presented stimuli number) for stimuli sets of three (ERM: $t(15) = 5.23$, $p < 6E\text{-}05$; LRA: $t(15) = 4.79$, $p < 0.0002$; Avg.: $t(15) = 5.40$, $p < 4E\text{-}05$) and four (ERM: $t(15) = 8.60$, $p < 2E\text{-}07$; LRA: $t(15) = 6.80$, p

<3E-06; Avg.: t(15) =8.31, p <3E-07).

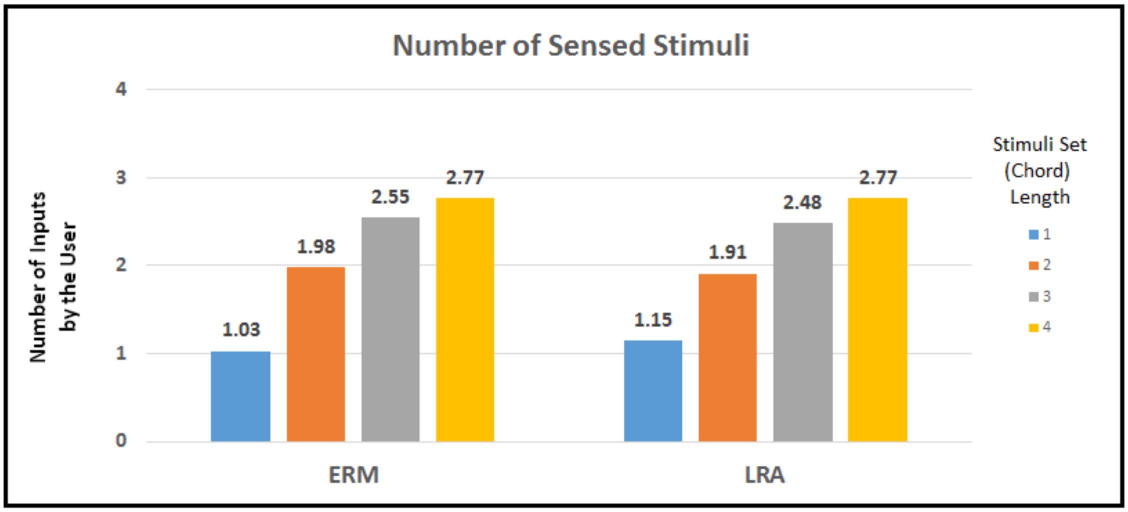


Figure A.5: Average number of stimuli entered (sensed) grouped by actual number of stimuli and by motor type (which pair of gloves).

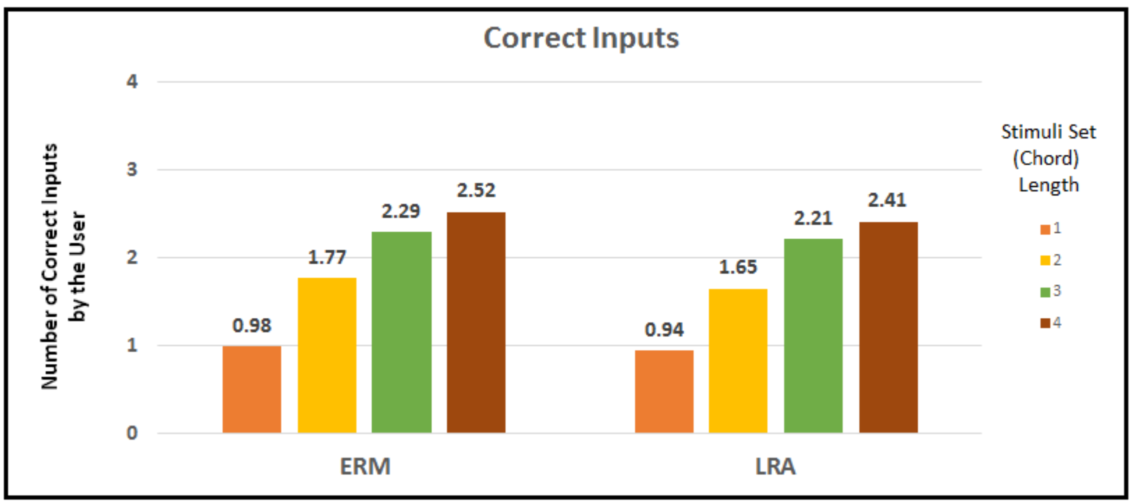


Figure A.6: Correct content (average number of correctly identified stimulus points) by number of stimuli in the chord. Graph represents the correct/usable data perceived, regardless of other incorrect or missing user responses to that chord.

Points Correct (Content) For each set size, we calculate the average number of points in each user response that are actually correct. This metric gives a sense of the content that users correctly perceive. Results show that content is lost or incorrectly sensed by participants for all chord lengths. T-tests confirm significant deviation from expected ground truth content scores, for all stimuli set lengths (one through four), for both motor types used. In addition to incorrect counting judgments Figure A.6 illustrates that the stimuli placements are often incorrectly identified. Thus, the usability of simultaneous tactile stimuli on the fingers is dubious due to the average 20-40% loss of data in every chord, regardless of which of the two motor types we used.

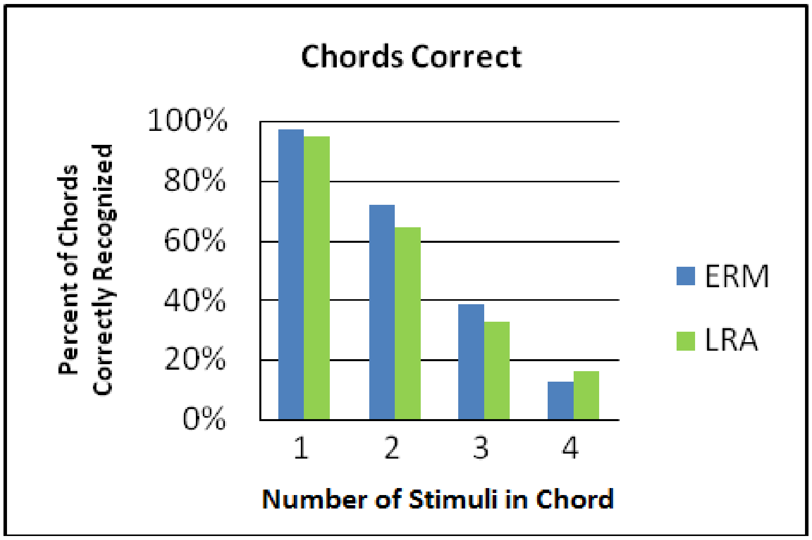


Figure A.7: Percentage of chords recognized without any error (100% of stimuli presented were recognized and identified), for chords of different numbers of stimuli.

Chords Correct User answers that exactly match the stimuli just presented are counted as totally correct. We calculated the percentage of totally correct answers for each chord (stimuli set) size and present this data in Figure A.7. While chords of one and two stimuli maintain average accuracies of over 65%, correct recognition of all points in chords of three and four was less than 40% and less than 20% respectively.

Examination of whether there were better-sensed locations for chorded stimuli points indicated no significant differences. Figure A.8 depicts these findings. As illustrated, identification accuracy for each point drops by an average of 50% when in conjunction with other simultaneous stimuli, independent of motor location (alone M=93%, SE=0.0085 vs. in chord M=42%, SE=0.0093). T-tests suggest that this difference is significant ($t(15)=39.21$, $p < 1E-06$).

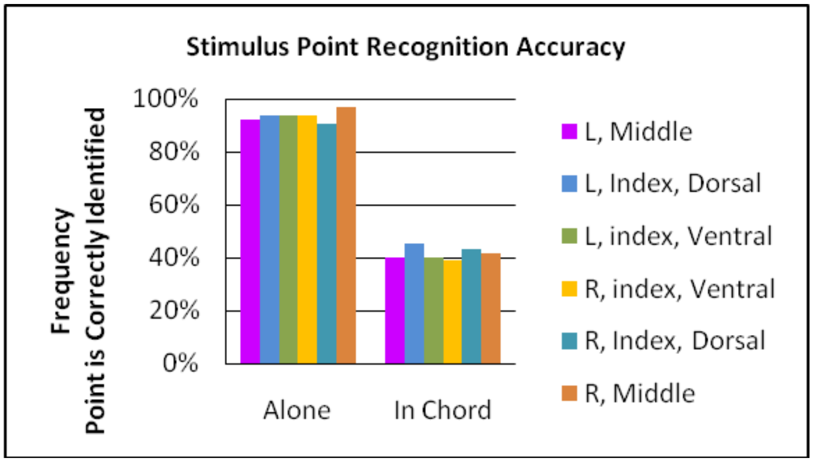


Figure A.8: Recognition accuracy by stimulus location – when stimulus is alone versus when it comes simultaneously with other stimuli.

Motor Comparison Findings in this Study We also contrast results produced using the ERM and the LRA gloves in this experiment to help use decide what part type to integrate into our system. Contrary to expectation, the gloves with embedded LRA motors provide no significant benefit to numerosity judgments or localization/identification of stimulus points. Users exhibit similar performance for both motor types in counting judgments for all stimulus set sizes, and t-tests indicate that any performance differences are not significant. LRA motors again provide no significant performance difference with respect to ERM motors when comparing correct points (chord content) in chords of three or four, and they actually provide significantly fewer correct stimuli identified when users receive one or two simultaneous stimuli (paired t-test: single stimulus $t(15)=2.07$, $p<0.0281$, two-stimuli sets $t(15)=2.41$, $p<0.0148$). Comparing total-chord recognition performance differences across the two glove pairs is again not significant for chorded stimuli, and the ERM gloves again outpace the LRA gloves for recognition of single stimuli. T-tests reveal performance differences between the two motor types to be significant ($t(15)=2.52$, $p<0.0118$).

Discussion

This study's results elucidate details in simultaneous tactile perception on the hands; most importantly they indicate that grouped stimuli cannot be delivered simultaneously if discrete perception is desired. Results are summarized in Figure A.7, representing user performances on chords of different numbers of stimuli. As indicated by this data, human perception of multiple simultaneous tactile stimuli points is poor, particularly for sets of three or more stimuli. Due to content loss found in each chord set (missed or mis-identified stimuli), effective chorded stimuli delivery is not possible in either glove pair studied. Whether the interface's application values stimuli counting or localization, neither appears achievable via simultaneous tactile stimuli. In regards to counting judgments, the significant error present in sets of more than two stimuli suggests against subitizing–in contrast to human visual perception of simultaneous points and notably consistent with findings of no subitizing in counting judgments of tactile stimuli across the full body [49]. Users typically fail to report one stimuli point in the three- and four-stimuli chords, as opposed to misidentification of a point's location. This result may be because of sensory funneling on the hands due to the density of stimuli points or activation of sensory fibers with large receptive fields. Human perception of multiple simultaneous tactile stimuli on the hands is poor. Simultaneous stimuli present a challenge to developers, designers and users, even when the user is focused on correct perception.

Conclusion

Simultaneous vibrotactile stimulation on the fingers is difficult to perceive, but offseting the activation of the motors with a small time delay is sufficient to allow for distinct recognition.

REFERENCES

[1] *Ab-004 : Understanding erm vibration motor characteristics*, Online. `https://www.precisionmicrodrives.com/content/ab-004-understanding-erm-vibration-motor-characteristics/`.

[2] A. F. Abercromby, W. E. Amonette, C. S. Layne, B. K. Mcfarlin, M. R. Hinman, and W. H. Paloski, "Variation in neuromuscular responses during acute whole-body vibration exercise," *Medicine & Science in Sports & Exercise*, vol. 39, no. 9, pp. 1642–1650, 2007.

[3] J. E. Aman, N. Elangovan, I.-L. Yeh, and J. Konczak, "The effectiveness of proprioceptive training for improving motor function: A systematic review," *Frontiers in human neuroscience*, vol. 8, 2014.

[4] D. Anson, *Top ten rehab technologies*, `https://resna.stanford.edu/TopTen/index.htm`, Rehabilitation Engineering and Assistive Technology Society of North America. Accessed: 03-17-2019.

[5] S. L. Beilock, T. H. Carr, C. MacMahon, and J. L. Starkes, "When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills.," *Journal of Experimental Psychology: Applied*, vol. 8, no. 1, p. 6, 2002.

[6] R. Bertani, C. Melegari, C Maria, A. Bramanti, P. Bramanti, and R. S. Calabrò, "Effects of robot-assisted upper limb rehabilitation in stroke patients: A systematic review with meta-analysis," *Neurological Sciences*, vol. 38, no. 9, pp. 1561–1569, 2017.

[7] X. Bi, B. A. Smith, and S. Zhai, "Quasi-qwerty soft keyboard optimization," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 2010, pp. 283–286.

[8] R. to the Nation by the National Federation of the Blind, "The braille literacy crisis in america: Facing the truth, reversing the trend, empowering the blind," 2009.

[9] *Braille instruction strategies*, `http://www.pathstoliteracy.org/instructional-strategies-teaching-braille`, Perkins School for the Blind's Paths to Literacy. Accessed: 03-17-2019.

[10] *Braille literacy*, http://www.cnib.ca/en/living/braille/literacy/Pages/default.aspx, Canadian National Institute for the Blind. 2014. Accessed: 03-17-2019.

[11] S. Brewster, F. Chohan, and L. Brown, "Tactile feedback for mobile interactions," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, San Jose, California, USA: ACM, 2007, pp. 159–162, ISBN: 978-1-59593-593-9.

[12] R. W. Brown, "The relation between two methods of learning piano music.," *Journal of Experimental Psychology*, vol. 16, no. 3, p. 435, 1933.

[13] T. A. Bullock, L. C. Schmertzing, and D. E. Center, "Instructional experiences of fifth grade students with keyboarding instruction," *PDF accessed on November*, vol. 1, 2010.

[14] D. Burke, K.-E. Hagbarth, L Löfstedt, and B. G. Wallin, "The responses of human muscle spindle endings to vibration of non-contracting muscles.," *The Journal of physiology*, vol. 261, no. 3, pp. 673–693, 1976.

[15] P. Caliandro, C. Celletti, L. Padua, I. Minciotti, G. Russo, G. Granata, G. La Torre, E. Granieri, and F. Camerota, "Focal muscle vibration in the treatment of upper limb spasticity: A pilot randomized controlled trial in patients with chronic stroke," *Archives of physical medicine and rehabilitation*, vol. 93, no. 9, pp. 1656–1661, 2012.

[16] H. Cammann, P. Stolz, and M. Wölfel, "Non-visual pedestrian navigation using vibrotactile stimuli in the wristband of a smartwatch,"

[17] M. Campbell, *Watch Effect: Scaling up Apple's Taptic Engine for iPhone and iPad*, http://appleinsider.com/articles/15/05/30/watch-effect-scaling-up-apples-taptic-engine-for-iphone-and-ipad, Accessed: 2018, 2015.

[18] J. R. Cauchard, J. L. Cheng, T. Pietrzak, and J. A. Landay, "Activibe: Design and evaluation of vibrations for progress monitoring," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, ACM, 2016, pp. 3261–3271.

[19] M. R. Chambers, K. Andres, M. v. Duering, and A Iggo, "The structure and function of the slowly adapting type ii mechanoreceptor in hairy skin," *Quarterly journal of experimental physiology and cognate medical sciences*, vol. 57, no. 4, pp. 417–445, 1972.

[20] C. S. Charlton, M. C. Ridding, P. D. Thompson, and T. S. Miles, "Prolonged peripheral nerve stimulation induces persistent changes in excitability of human motor cortex," *Journal of the neurological sciences*, vol. 208, no. 1-2, pp. 79–85, 2003.

[21] B. Chwirka, B. Gurney, and P. A. Burtner, "Keyboarding and visual-motor skills in elementary students: A pilot study," *Occupational Therapy in Health Care*, vol. 16, no. 2-3, pp. 39–51, 2002.

[22] J. M. Clark and A. Paivio, "Dual coding theory and education," *Educational psychology review*, vol. 3, no. 3, pp. 149–210, 1991.

[23] E. Clarkson, J. Clawson, K. Lyons, and T. Starner, "An empirical study of typing rates on mini-qwerty keyboards," in *CHI extended abstracts on Human factors in computing systems*, ACM, 2005, pp. 1288–1291.

[24] R. J. Coffey, D. Cahill, W. Steers, T. Park, J. Ordia, J. Meythaler, R. Herman, A. G. Shetter, R. Levy, B. Gill, *et al.*, "Intrathecal baclofen for intractable spasticity of spinal origin: Results of a long-term multicenter study," *Journal of neurosurgery*, vol. 78, no. 2, pp. 226–232, 1993.

[25] T. R. Coles, D. Meglan, and N. W. John, "The role of haptics in medical training simulators: A survey of the state of the art," *IEEE Transactions on haptics*, vol. 4, no. 1, pp. 51–66, 2011.

[26] A. B. Conforto, A. Kaelin-Lang, and L. G. Cohen, "Increase in hand muscle strength of stroke patients after somatosensory stimulation," *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, vol. 51, no. 1, pp. 122–125, 2002.

[27] M. O. Conrad, R. A. Scheidt, and B. D. Schmit, "Effects of wrist tendon vibration on targeted upper-arm movements in poststroke hemiparesis," *Neurorehabilitation and neural repair*, vol. 25, no. 1, pp. 61–70, 2011.

[28] W. E. Cooper, *Cognitive aspects of skilled typewriting*. Springer Science & Business Media, 1983.

[29] P. Cordo, H. Lutsep, L. Cordo, W. G. Wright, T. Cacciatore, and R. Skoss, "Assisted movement with enhanced sensation (ames): Coupling motor and sensory to remediate motor deficits in chronic stroke patients," *Neurorehabilitation and neural repair*, vol. 23, no. 1, pp. 67–77, 2009.

[30] P. Cordo, S. Wolf, J.-S. Lou, R. Bogey, M. Stevenson, J. Hayes, and E. Roth, "Treatment of severe hand impairment following stroke by combining assisted movement, muscle vibration, and biofeedback," *Journal of Neurologic Physical Therapy*, vol. 37, no. 4, pp. 194–203, 2013.

[31] I. S. Corry, A. P. Cosgroce, E. Walsh, D McClean, and H. Graham, "Botulinum toxin a in the hemiplegia upper limb: A double-blind trial," *Developmental Medicine & Child Neurology*, vol. 39, no. 3, pp. 185–193, 1997.

[32] L. M. Crespo and D. J. Reinkensmeyer, “Haptic guidance can enhance motor learning of a steering task,” *Journal of motor behavior*, vol. 40, no. 6, pp. 545–557, 2008.

[33] T Curran and D. Schacter, *Implicit Learning and Memory: Psychological and Neural Aspects*. Elsevier, 2001.

[34] P. Dajpratham, V. Kuptniratsaikul, A. Kovindha, P. S.-a. Kuptniratsaikul, and K. Dejnuntarat, “Prevalence and management of poststroke spasticity in thai stroke patients: A multicenter study,” *Medical journal of the Medical Association of Thailand*, vol. 92, no. 10, p. 1354, 2009.

[35] A. Das and W. Stuerzlinger, “A cognitive simulation model for novice text entry on cell phone keypads,” in *Proceedings of the 14th European conference on Cognitive ergonomics: invent! explore!*, ACM, 2007, pp. 141–147.

[36] C. Delecluse, M. Roelants, and S. Verschueren, “Strength increase after whole-body vibration compared with resistance training,” *Medicine & Science in Sports & Exercise*, vol. 35, no. 6, pp. 1033–1041, 2003.

[37] V. Dietz and T. Sinkjaer, “Spasticity,” in *Handbook of clinical neurology*, vol. 109, Elsevier, 2012, pp. 197–211.

[38] S. Doyle, S. Bennett, S. E. Fasoli, and K. T. McKenna, “Interventions for sensory impairment in the upper limb after stroke,” *Cochrane Database of Systematic Reviews*, no. 6, 2010.

[39] R. A. Duke, A. L. Simmons, and C. D. Cash, “It’s not how much; it’s how: Characteristics of practice behavior and retention of performance skills,” *Journal of Research in Music Education*, vol. 56, no. 4, pp. 310–321, 2009.

[40] D Dweitschenko, “Materialen zur frage de knochensensibilitat,” *Neur.. Centralb*, vol. 19, pp. 430–431, 1900.

[41] *Effects of stroke*, `http://www.strokeassociation.org/STROKEORG/AboutStroke/EffectsofStroke/Effects-of-Stroke_UCM_308534_SubHomePage.jsp`, American Heart Association. 2012. Accessed: 03-17-2019.

[42] M. Fahle, “Perceptual learning: Gain without pain?” *Nature neuroscience*, vol. 5, no. 10, p. 923, 2002.

[43] J. B. Fallon and V. G. Macefield, “Vibration sensitivity of human muscle spindles and golgi tendon organs,” *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, vol. 36, no. 1, pp. 21–29, 2007.

[44] L. Fattorini, A. Ferraresi, A. Rodio, G. B. Azzena, and G. M. Filippi, "Motor performance changes induced by muscle vibration," *European journal of applied physiology*, vol. 98, no. 1, pp. 79–87, 2006.

[45] D. Feygin, M. Keehner, and R Tendick, "Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill," in *Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS*, IEEE, 2002, pp. 40–47.

[46] A. Forner-Cordero, M. Steyvers, O. Levin, K. Alaerts, and S. P. Swinnen, "Changes in corticomotor excitability following prolonged muscle tendon vibration," *Behavioural brain research*, vol. 190, no. 1, pp. 41–49, 2008.

[47] *Fritz! online game*, `www.gamesgames.com/game/fitz`, Accessed: 08-30-2014.

[48] T. Gaertner, *Hands together*, `http://trainingthemusicalbrain.blogspot.com/2012/03/hands-together.html`, Training The Musical Brain: a Neuroscience Perspective on Teaching and Learning Music. Accessed: 03-17-2019., 2012.

[49] A. Gallace, H. Z. Tan, and C. Spence, "Can tactile stimuli be subitised? an unresolved controversy within the literature on numerosity judgments," *Perception*, vol. 37, no. 5, pp. 782–800, 2008.

[50] M. Giordano and M. M. Wanderley, "Perceptual and technological issues in the design of vibrotactile-augmented interfaces for music technology and media," in *International Workshop on Haptic and Audio Interaction Design*, Springer, 2013, pp. 89–98.

[51] S. M. Golaszewski, J. Bergmann, M. Christova, A. B. Kunz, M. Kronbichler, D. Rafolt, E. Gallasch, W. Staffen, E. Trinka, and R. Nardone, "Modulation of motor cortex excitability by different levels of whole-hand afferent electrical stimulation," *Clinical Neurophysiology*, vol. 123, no. 1, pp. 193–199, 2012.

[52] I Gordon, "The sensation of vibration, with special reference to its clinical significance," *Journal of Neurology and Psychopathology*, vol. 17, no. 66, p. 107, 1936.

[53] V. M. Grant, A. Gibson, and N. Shields, "Somatosensory stimulation to improve hand and upper limb function after strokea systematic review with meta-analyses," *Topics in stroke rehabilitation*, vol. 25, no. 2, pp. 150–160, 2018.

[54] N. Green, J. Kruger, C. Faldu, and R. St Amant, "A reduced qwerty keyboard for mobile text entry," in *CHI'04 extended abstracts on Human factors in computing systems*, ACM, 2004, pp. 1429–1432.

[55] G. C. Grindlay, “The impact of haptic guidance on musical motor learning,” PhD thesis, Massachusetts Institute of Technology, 2007.

[56] F. R. Group, “Optimizing ability of message receipt by people with disabilities: Prototype findings report/vibration scale final report,” *Dept. of Homeland Security*, 2017.

[57] J. K. Harpole, *5 Things you Should Know Before you Consider Court Reporting School*, `https://stenofabulous.com/2015/01/5-things-you-should-know-before-you-consider-court-reporting-school`, Accessed: 2017-4-24, 2015.

[58] L. S. Hartman, *Handwriting / Keyboarding Rates*, `http://www.qiat.org/docs/resourcebank/hwriting_kybding_rate_info.pdf`, 2005. Accessed: 2017-4-24.

[59] K. Huang, E. Y.-L. Do, and T. Starner, “Pianotouch: A wearable haptic piano instruction system for passive learning of piano skills,” in *Proceedings of the International Symposium on Wearable Computers (ISWC)*, IEEE, 2008, pp. 41–44.

[60] K. Huang, T. Starner, E. Do, G. Weiberg, D. Kohlsdorf, C. Ahlrichs, and R. Leibrandt, “Mobile music touch: Mobile tactile stimulation for passive learning,” in *Proceedings of the SIGCHI conference on human factors in computing systems*, ACM, 2010, pp. 791–800.

[61] *Impact of stroke (stroke statistics)*, `http://www.strokeassociation.org/STROKEORG/AboutStroke/Impact-of-Stroke-Stroke-statistics_UCM_310728_Article.jsp#.WcNYyMaJjX4`, American Heart Association. Accessed: 03-17-2019.

[62] *Iphone, smartphone, mobile, screen, technology. creative commons cc0 public domain.* `https://pxhere.com/en/photo/930755`, Accessed: 03-17-2019.

[63] N. Jafari, K. D. Adams, and M. Tavakoli, “Haptics to improve task performance in people with disabilities: A review of previous studies and a guide to future research with children with disabilities,” *Journal of Rehabilitation and Assistive Technologies Engineering*, vol. 3, p. 2 055 668 316 668 147, 2016.

[64] P. Jarvis, J. Holford, and C. Griffin, *The theory & practice of learning*. Psychology Press, 2003.

[65] S. Je, B. Rooney, L. Chan, and A. Bianchi, “Tactoring: A skin-drag discrete display,” in *Proceedings of the CHI Conference on Human Factors in Computing Systems*, ACM, 2017, pp. 3106–3114.

[66] G. Jenkins, *Hanging Out with America's Elite, Underappreciated Court Reporters*, https://www.vice.com/en_us/article/hanging-out-with-americas-elite-underappreciated-court-reporters-812, Accessed: 2017-4-24, 2015.

[67] L. Jiang, R. Girotra, M. R. Cutkosky, and C. Ullrich, "Reducing error rates with low-cost haptic feedback in virtual reality-based training applications," in *Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. 2005.*, IEEE, pp. 420–425.

[68] R. S. Johansson and Å. B. Vallbo, "Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin.," *The Journal of physiology*, vol. 286, no. 1, pp. 283–300, 1979.

[69] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Current opinion in neurobiology*, vol. 11, no. 4, pp. 455–461, 2001.

[70] R. M. Johnson, J. van der Linden, and Y. Rogers, "Musicjacket: The efficacy of real-time vibrotactile feedback for learning to play the violin," in *CHI'10 Extended Abstracts on Human Factors in Computing Systems*, ACM, 2010, pp. 3475–3480.

[71] A. Kaelin-Lang, A. R. Luft, L. Sawaki, A. H. Burstein, Y. H. Sohn, and L. G. Cohen, "Modulation of human corticomotor excitability by somatosensory input," *The Journal of physiology*, vol. 540, no. 2, pp. 623–633, 2002.

[72] A. Karpur, *The Haptic Breakdown: Whats Inside Your Smartwatch, Somatic Labs*, https://blog.somaticlabs.io/the-haptic-breakdown-whats-inside-your-smartwatch/, Accessed: 2018, 2015.

[73] D. Kohlsdorf and T. Starner, "Mobile music touch: The effect of primary tasks on passively learning piano sequences," in *Wearable Computers (ISWC), 2010 International Symposium on*, IEEE, 2010, pp. 1–8.

[74] P. O. Kristensson, "Five challenges for intelligent text entry methods," *AI Magazine*, vol. 30, no. 4, p. 85, 2009.

[75] H. E. Krugman and E. L. Hartley, "Passive learning from television," *Public Opinion Quarterly*, vol. 34, no. 2, pp. 184–190, 1970.

[76] K. J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving contact realism through event-based haptic feedback," *Transactions on visualization and computer graphics*, vol. 12, no. 2, pp. 219–230, 2006.

[77] T. Kuhlin, *Considering a career change to become a court reporter*, http://suite101.com/article/considering-a-careerchange-to--

become-a-court-reporter-a370134, Suite101. 2009. Accessed: 03-17-2019.

[78] S. C. Lee and T. Starner, “Buzzwear: Alert perception in wearable tactile displays on the wrist,” in *Proceedings of the SIGCHI conference on Human factors in computing systems*, ACM, 2010, pp. 433–442.

[79] V. Lehtinen, A. Oulasvirta, A. Salovaara, and P. Nurmi, “Dynamic tactile guidance for visual search tasks,” in *Proceedings of the 25th annual ACM symposium on User interface software and technology*, ACM, 2012, pp. 445–452.

[80] C. E. Lewiston, “Magkeys: A haptic guidance keyboard system for facilitating sensorimotor training and rehabilitation,” PhD thesis, Citeseer, 2008.

[81] J Liepert, W. Miltner, H Bauder, M Sommer, C Dettmers, E Taub, and C Weiller, “Motor cortex plasticity during constraint-induced movement therapy in stroke patients,” *Neuroscience letters*, vol. 250, no. 1, pp. 5–8, 1998.

[82] *Linear resonant actuator (lra) vibration motors :: Haptic feedback*, Online. https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/.

[83] A. R. Luft, A. Kaelin-Lang, T.-K. Hauser, M. M. Buitrago, N. V. Thakor, D. F. Hanley, and L. G. Cohen, “Modulation of rodent cortical motor excitability by somatosensory input,” *Experimental brain research*, vol. 142, no. 4, pp. 562–569, 2002.

[84] J. Lüttgen and H. Heuer, “The influence of robotic guidance on different types of motor timing,” *Journal of motor behavior*, vol. 45, no. 3, pp. 249–258, 2013.

[85] G. Luzhnica, E. Veas, and C. Seim, “Passive haptic learning for vibrotactile skin reading,” in *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, ACM, 2018, pp. 40–43.

[86] J. V. Lynskey, A. Belanger, and R. Jung, “Activity-dependent plasticity in spinal cord injury,” *Journal of rehabilitation research and development*, vol. 45, no. 2, p. 229, 2008.

[87] K. Lyons, D. Plaisted, and T. Starner, “Expert chording text entry on the twiddler one-handed keyboard,” in *Proceedings of the International Symposium on Wearable Computers (ISWC)*, IEEE, vol. 1, 2004, pp. 94–101.

[88] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, “A survey on robotic devices for upper limb rehabilitation,” *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, p. 3, 2014.

[89] I. S. MacKenzie and K. Tanaka-Ishii, *Text entry systems: Mobility, accessibility, universality*. Morgan Kaufmann, 2010.

[90] L. Marchal-Crespo, M. van Raai, G. Rauter, P. Wolf, and R. Riener, "The effect of haptic guidance and visual feedback on learning a complex tennis task," *Experimental brain research*, vol. 231, no. 3, pp. 277–291, 2013.

[91] B. Marconi, G. M. Filippi, G. Koch, V. Giacobbe, C. Pecchioli, V. Versace, F. Camerota, V. M. Saraceni, and C. Caltagirone, "Long-term effects on cortical excitability and motor recovery induced by repeated muscle vibration in chronic stroke patients," *Neurorehabilitation and neural repair*, vol. 25, no. 1, pp. 48–60, 2011.

[92] T. Markow, N. Ramakrishnan, K. Huang, T. Starner, M. Eicholtz, S. Garrett, H. Profita, A. Scarlata, C. Schooler, A. Tarun, *et al.*, "Mobile music touch: Vibration stimulus in hand rehabilitation," in *Pervasive Computing Technologies for Healthcare (PervasiveHealth), 2010 4th International Conference on-NO PERMISSIONS*, IEEE, 2010, pp. 1–8.

[93] T. T. Markow, "Mobile music touch: Using haptic stimulation for passive rehabilitation and learning," PhD thesis, Georgia Institute of Technology, 2012.

[94] E. Matias, I. S. MacKenzie, and W. Buxton, "Half-qwerty: A one-handed keyboard facilitating skill transfer from qwerty," in *Proceedings of the INTERACT and CHI Conference on Human Factors in Computing Systems*, ACM, 1993, pp. 88–94.

[95] E. Matias, I. S. MacKenzie, and W. Buxton, "Half-qwerty: A one-handed keyboard facilitating skill transfer from qwerty," in *Proceedings of the INTERACT'93 and CHI'93 Conference on Human Factors in Computing Systems*, ACM, 1993, pp. 88–94.

[96] E. Matias, I. S. MacKenzie, and W. Buxton, "One-handed touch typing on a qwerty keyboard," *Human-Computer Interact.*, vol. 11, no. 1, pp. 1–27, Mar. 1996.

[97] C. McCarthy, "Morse code: A staple in the navy iw toolkit," in *https://www.dvidshub.net/news/1873 code-staple-navy-iw-toolkit*, Center for Information Dominance, Center for Information Warfare Training, 2016.

[98] *Morse code at 140 wpm*, `http://www.arrl.org/news/morse-code-at-140-wpm`, National Assoc. for Amateur Radio. 2008.

[99] *Musical glove improves sensation for people with spinal cord injury*, `http://arts.gatech.edu/content/musical-glove-improves-sensation-mobility-people-spinal-cord-injury`, Accessed: 03-17-2019.

[100] L. L. Ness and E. C. Field-Fote, "Effect of whole-body vibration on quadriceps spasticity in individuals with spastic hypertonia due to spinal cord injury," *Restorative neurology and neuroscience*, vol. 27, no. 6, pp. 623–633, 2009.

[101] T. Noma, S. Matsumoto, S. Etoh, M. Shimodozono, and K. Kawahira, "Anti-spastic effects of the direct application of vibratory stimuli to the spastic muscles of hemiplegic limbs in post-stroke patients," *Brain Injury*, vol. 23, no. 7-8, pp. 623–631, 2009.

[102] A. M. Okamura, J. T. Dennerlein, and R. D. Howe, "Vibration feedback models for virtual environments," in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, IEEE, vol. 1, 1998, pp. 674–679.

[103] K. Ollivier-Lanvin, B. E. Keeler, R. Siegfried, J. D. Houlé, and M. A. Lemay, "Proprioceptive neuropathy affects normalization of the h-reflex by exercise after spinal cord injury," *Experimental neurology*, vol. 221, no. 1, pp. 198–205, 2010.

[104] S. J. Page, D. R. Gater, and P. Bach-y Rita, "Reconsidering the motor recovery plateau in stroke rehabilitation," *Archives of physical medicine and rehabilitation*, vol. 85, no. 8, pp. 1377–1381, 2004.

[105] M. Paoloni, M. Mangone, P. Scettri, R. Procaccianti, A. Cometa, and V. Santilli, "Segmental muscle vibration improves walking in chronic stroke patients with foot drop: A randomized controlled trial," *Neurorehabilitation and neural repair*, vol. 24, no. 3, pp. 254–262, 2010.

[106] M. Paoloni, E. Tavernese, M. Fini, P. Sale, M. Franceschini, V. Santilli, and M. Mangone, "Segmental muscle vibration modifies muscle activation during reaching in chronic stroke: A pilot study," *NeuroRehabilitation*, vol. 35, no. 3, pp. 405–414, 2014.

[107] T Platz, "Impairment-oriented training (iot)–scientific concept and evidence-based treatment strategies," *Restorative neurology and neuroscience*, vol. 22, no. 3-5, pp. 301–315, 2004.

[108] R. Powers, J Marder-Meyer, and W. Rymer, "Quantitative relations between hypertonia and stretch reflex threshold in spastic hemiparesis," *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, vol. 23, no. 2, pp. 115–124, 1988.

[109] P. Raghavan, "The nature of hand motor impairment after stroke and its treatment," *Current treatment options in cardiovascular medicine*, vol. 9, no. 3, pp. 221–228, 2007.

[110] S. M. Rao, A. R. Mayer, and D. L. Harrington, “The evolution of brain activation during temporal processing,” *Nature neuroscience*, vol. 4, no. 3, p. 317, 2001.

[111] A. Reber, *Psychology of Tacit Knowledge*. Elsevier, 2001.

[112] J. Rittweger, “Vibration as an exercise modality: How it may work, and what its potential might be,” *European journal of applied physiology*, vol. 108, no. 5, pp. 877–904, 2010.

[113] E. M. Robertson, “The serial reaction time task: Implicit motor skill learning?” *Journal of Neuroscience*, vol. 27, no. 38, pp. 10 073–10 075, 2007.

[114] E. M. Rogers, *Diffusion of innovations*. Simon and Schuster, 2010.

[115] H. Rogers, J. Laehn, A. Lang, D. OLeary, and M. Sommers, “The status of elementary keyboarding: A longitudinal study,” *Unpublished research study, Whitewater, WI: UW-Whitewater*, 2003.

[116] J. Rogers and J. Case-Smith, “Relationships between handwriting and keyboarding performance of sixth-grade students,” *American Journal of Occupational Therapy*, vol. 56, no. 1, pp. 34–39, 2002.

[117] K. Rosenkranz and J. C. Rothwell, “Differential effect of muscle vibration on intracortical inhibitory circuits in humans,” *The Journal of physiology*, vol. 551, no. 2, pp. 649–660, 2003.

[118] G. Rubin-Rabson, “Studies in the psychology of memorizing piano music: Ii. a comparison of massed and distributed practice.,” *Journal of Educational Psychology*, vol. 31, no. 4, p. 270, 1940.

[119] J. Sargent, S. Dopkins, J. Philbeck, and D. Chichka, “Chunking in spatial memory.,” *Journal of Experimental Psychology: Learning, memory, and cognition*, vol. 36, no. 3, p. 576, 2010.

[120] C. Seim, J. Chandler, K. DesPortes, S. Dhingra, M. Park, and T. Starner, “Passive haptic learning of braille typing,” in *Proceedings of the 2014 ACM International Symposium on Wearable Computers*, ACM, 2014, pp. 111–118.

[121] C. Seim, N. Doering, Y. Zhang, W. Stuerzlinger, and T. Starner, “Passive haptic training to improve speed and performance on a keypad,” *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 1, no. 3, p. 100, 2017.

[122] C. Seim, T. Estes, and T. Starner, “Towards passive haptic learning of piano songs,” in *World Haptics Conference (WHC).*, IEEE, 2015, pp. 445–450.

[123] C. Seim, J. Hallam, S. Raghu, T.-A. Le, G. Bishop, and T. Starner, "Perception in hand-worn haptics: Placement, simultaneous stimuli, and vibration motor comparisons," Georgia Institute of Technology, Tech. Rep., 2015.

[124] C. Seim, R. Pontes, S. Kadiveti, Z. Adamjee, A. Cochran, T. Aveni, P. Presti, and T. Starner, "Towards haptic learning on a smartwatch," in *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, ACM, 2018, pp. 228–229.

[125] C. Seim, S. Reynolds-Haertle, S. Srinivas, and T. Starner, "Tactile taps teach rhythmic text entry: Passive haptic learning of morse code," in *Proceedings of the International Symposium on Wearable Computers*, ACM, 2016, pp. 164–171.

[126] C. E. Seim, D. Quigley, and T. E. Starner, "Passive haptic learning of typing skills facilitated by wearable computers," in *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, ACM, 2014, pp. 2203–2208.

[127] C. H. Shea, Q. Lai, C. Black, and J.-H. Park, "Spacing practice sessions across days benefits the learning of motor skills," *Human movement science*, vol. 19, no. 5, pp. 737–760, 2000.

[128] G Sheean, "The pathophysiology of spasticity," *European journal of neurology*, vol. 9, pp. 3–9, 2002.

[129] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review," *Psychonomic Bulletin & Review*, vol. 20, no. 1, pp. 21–53, 2013.

[130] C. Southern, J. Clawson, B. Frey, G. Abowd, and M. Romero, "An evaluation of brailletouch: Mobile touchscreen text entry for the visually impaired," in *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, ACM, 2012, pp. 317–326.

[131] D. Spelmezan, "An investigation into the use of tactile instructions in snowboarding," in *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, ACM, 2012, pp. 417–426.

[132] D. Spelmezan, D. R. Sahoo, and S. Subramanian, "Sparkle: Hover feedback with touchable electric arcs," in *Proceedings of the CHI Conference on Human Factors in Computing Systems*, ACM, 2017, pp. 3705–3717.

[133] R. Stansifer, *The midi file format*, `http://cs.fit.edu/~ryan/cse4051/projects/midi/midi.html`, Accessed: 03-17-2019.

[134] T. Starner, "How wearables worked their way into the mainstream," *IEEE Pervasive Computing*, vol. 13, no. 4, pp. 10–15, 2014.

[135] E. Strasnick, J. R. Cauchard, and J. A. Landay, “Brushtouch: Exploring an alternative tactile method for wearable haptics,” in *Proceedings of the CHI Conference on Human Factors in Computing Systems*, ACM, 2017, pp. 3120–3125.

[136] *Stroke, cerebrovascular accident*, `http://www.who.int/topics/cerebrovascular_accident/en/`, World Health Organization.

[137] H. Tan, R. Gray, J. J. Young, and R. Taylor, “A haptic back display for attentional and directional cueing,” *Haptics-e, The electronic journal of haptics research*, 2003.

[138] H. W. Tappeiner, R. L. Klatzky, B. Unger, and R. Hollis, “Good vibrations: Asymmetric vibrations for directional haptic cues,” in *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, IEEE, 2009, pp. 285–289.

[139] *The need for braille*, `http://www.nbp.org/ic/nbp/braille/needforbraille.html`, National Braille Press. 2013.

[140] T. Thom, N. Haase, W. Rosamond, V. J. Howard, J. Rumsfeld, T. Manolio, Z.-J. Zheng, K. Flegal, C. O’donnell, S. Kittner, *et al.*, “Heart disease and stroke statistics–2006 update: A report from the american heart association statistics committee and stroke statistics subcommittee.,” *Circulation*, vol. 113, no. 6, e85, 2006.

[141] *Virtual reality headset and wired gloves.* `https://commons.wikimedia.org/wiki/File:Virtual_reality_headset_and_wired_gloves,_Ames_Research_Center.jpg`, NASA Ames Research Center. Creative Commons. Accessed: 03-17-2019.

[142] J. B. Wallace, “The effects of color-coding on keyboarding instruction of third grade students.,” *ERIC*, 2000.

[143] B. J. Waner K. and S. McCrary, “Two points of view on elementary school keyboarding.,” Business Education Forum, 1992, pp. 27–29.

[144] T. Watanabe, J. E. Náñez, and Y. Sasaki, “Perceptual learning without perception,” *Nature*, vol. 413, no. 6858, p. 844, 2001.

[145] T. Watanabe, J. E. Náñez Sr, S. Koyama, I. Mukai, J. Liederman, and Y. Sasaki, “Greater plasticity in lower-level than higher-level visual motion processing in a passive perceptual learning task,” *Nature neuroscience*, vol. 5, no. 10, p. 1003, 2002.

[146] C. K. Williams and H. Carnahan, “Motor learning perspectives on haptictraining for the upper extremities,” *Transactions on Haptics*, vol. 7, no. 2, pp. 240–250, 2014.

[147] S. L. Wolf, C. J. Winstein, J. P. Miller, E. Taub, G. Uswatte, D. Morris, C. Giuliani, K. E. Light, D. Nichols-Larsen, E. Investigators, *et al.*, “Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The excite randomized clinical trial,” *Jama*, vol. 296, no. 17, pp. 2095–2104, 2006.

[148] G. Wulf, “Attentional focus and motor learning: A review of 10 years of research,” *E-Journal Movement and Training*, 2007.

[149] G. Wulf, N. McNevin, and C. H. Shea, “The automaticity of complex motor skill learning as a function of attentional focus,” *The Quarterly Journal of Experimental Psychology: Section A*, vol. 54, no. 4, pp. 1143–1154, 2001.

[150] X. Yang, Y. K. Kim, Q. Wu, and Q. Chen, “Hand function training in haptic virtual environment,” in *Proceedings of the International Conference on Mechatronics and Automation*, IEEE, 2006, pp. 395–399.

[151] X.-D. Yang, W. F. Bischof, and P. Boulanger, “Validating the performance of haptic motor skill training,” *Haptic interfaces for virtual environment and teleoperator systems, 2008. World haptics symposium.*, pp. 129–135, 2008.

[152] *Your first two hand lesson for piano.* `http://www.get-piano-lessons.com/lesson-piano.html`, www.Get-Piano-Lessons.com.

[153] C. Zukin and R. Snyder, “Passive learning: When the media environment is the message,” *Public Opinion Quarterly*, vol. 48, no. 3, pp. 629–638, 1984.